SECTION IV

STATIC RELAYS

AND

STATIC PROTECTION SCHEMES

38-A

Introduction to Static and Microprocessor-based Integrated Programmable Protection, Monitoring and Control Systems

— Introduction to Static Relays and Integrated programmable Protective monitoring and control systems. Historical review — basic comparison, recent trends — Analogue Relays, Digital relays, Programmable Relays — Modular concept, Functional Modules and Assembly — Devices and components — Functional units in static relay system — Analogue circuits, Digital Circuits, Programmable Systems — AD Conversion — Applications of static relays — Components of Static Relays.

Ch. 25 gives Introduction to Protective Relaying. The principles described in Sec. 25.1 to 25.16 are applicable to Electromagnetic Relays and Static Relays. During 1980's Static relays and Microprocessor-based integrated, programmable protection, control and monitoring systems have been introduced. The versatile systems perform several tasks including monitoring, protection, data acquisition, display, control etc. Static relays and combined protection and control systems form an integral part of SCADA Systems. (Ch. 50)

38.1. INTRODUCTION AND DEFINITION

Static Relay (Solid State Relay) is an electrical relay in which the response is developed by electronic/magnetic/optical or other components, without mechanical motion of components.

Note. A relay which is composed of both static and electromechanical units in which the response is accomplished by static units is also called as a static relay.

In static relays, the measurement is performed by electronic/magnetic/optical or other components *without mechanical motion.* However additional electromechanical relay units may be used in output stage as auxiliary relays. *A protective system is formed by static relays and electromechanical auxiliary relays.*

Fig. 38.1 (*a*) illustrates the *essential components* in a static relays. The output of CT's of PT's or transducers is rectified in *rectifier.*

The rectified output is fed to the *measuring unit.* The measuring unit comprises comparators, level detectors, filters, logic circuits. *The output is initiated when input reaches the threshold value.*

The output of measuring unit is amplified by *Amplifier.*

The amplified output is given to the *output unit* which energizes the trip coil only when relay operates.

In conventional electromagnetic the measurement is carried out by comparing operating torque/force with restraining torque/force. The electro-mechanical relay operates when operating torque/force exceeds the restraining torque/force. The pick-up of relay is obtained by movement of movable element in the relay. In a static relay the measurement is performed by static circuits.

A simplified block diagram of single input static relay is given in Fig. 38.1 (*a*). In individual relays there is a wide variation. The quantities : voltage, current etc. is rectified and measured.

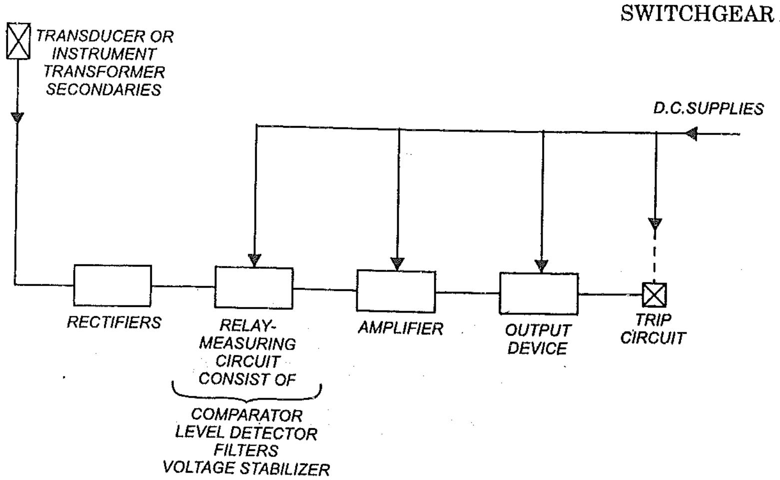


Fig. 38.1 (*a*). Block diagram of a static relay-simplified.

When the quantity to be measured reaches certain well defined value, the output device is triggered. Thereby current flows in the trip circuit of the circuit-breaker. Fig. 38.1 (*b*) gives a block diagram of a microprocessor based digital, programmable static relay.

Static relays can be arranged to respond to electrical inputs. The other forms of inputs such as heat, light, magnetic field, travelling waves etc. can be suitably converted into equivalent analogue or digital signals and then fed to the static relay. A multi-input static relay can accept several inputs. The logic circuit in the multi-input digital static relay can determine the conditions for relay response and sequence of events in the response.

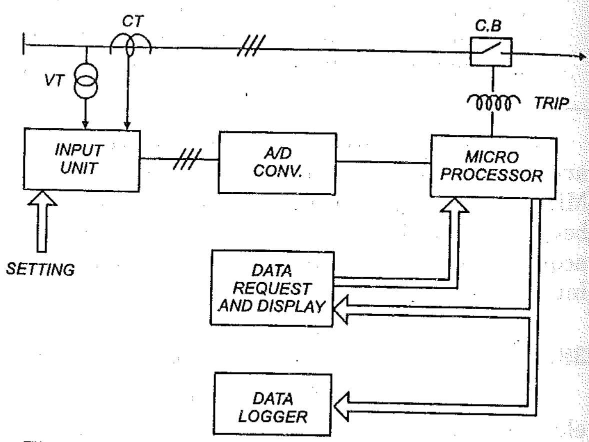


Fig. 38.1 (*b*). Block diagram of a simple Microprocessor Based Digital Static Relay.

A programmable protection and control system has a microprocessor or microcomputer in its circuit. *With the help of the logic circuits and the microprocessor the integrated protection and control system can perform several functions of data acquisition, data processing, data transmission, protection and control. Earlier, for each of these functions, separate electromechanical or static units were used along with complex wiring.*

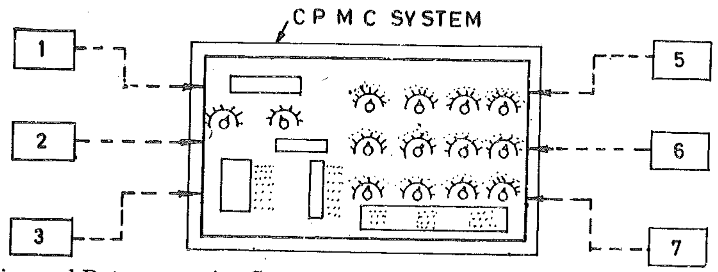
A *static relay* generally has several functional units. Some of the auxiliary functional units may be *electromechanical.*

The types of electronic circuits in static protection system include :

(1) Analogue circuits (2) Digital circuits (3) Hybrid circuits. For very simple functions, analogue circuits are preferred. For complex functions, digital circuits are preferred.

Advanced digital Static Relays may have Programmable System. Such relays are preferred for complex functions.

A *static relay may have one or more programmable units such as a microprocessor. Such relays are called programmable relays or microprocessor based relays or microprocessor controlled relays.* Programmable Static Relay system can perform several functions including protection, monitoring, data acquisition, control.



1. Data acquisition and Data processing System
2. Protection system
3. Control system
4. Data transmission system
5. Man-machine interface
6. Event recording
7. Additional required features.

Fig. 38.1 (*c*). Combined Protection, Monitoring and Control System (CPMC). CPMC has sub-systems (1 to 6) in a single unit.

An integrated static programmable protective and control system has one or more of the following subsytems (Fig. 38.1 (*c*)).

— Data acquisition and processing subsystem

— Protection system

— Control system

— Data transmission system

The required subsystems are assembled and mounted on a single panel to form an integrated modular programmable combined protection and control system. Fig. 38.1 (*c*) gives the concept of Combined Protection, Monitoring and Control System (CPMC) programmable system.

The total interconnected power system is managed by **Supervisory Control and Data Acquisition (SCADA) system, Energy Management Systems (EMS) and Automatic generation control systems (AGC).** *Integrated Protection and control programmable systems installed in generating station control rooms, substation control rooms and load control centres form the subsystems of the SCADA, EMS and AGC system. The programmable protection and control systems in different locations are linked by means of data transmission channels such as Power Line Carrier (PLC), Microwave, Fibre optic cables (For shorter lengths).*

The unit level has protective relays each of which performs one or more protective functions *e.g.* overcurrent protection, earth fault protection. Unit level is provided for each protected zone, *e.g.* bus zone, transformer zone, line zone.

At *substation or generating station level,* the microprocessor based system performs several protective functions and monitoring such as back up protection, autoreclosing sequence, sequential tripping, load shedding, remote signalling etc.

At *control centre level* the programmable system performs several functions of load management, load frequency control, planning operation, monitoring, economic loading, moral emergency and post-emergency actions.

In *electromechanical relays and systems,* a separate relay unit is required for each protective function. Several separate units are required in protective system of a greater or a large motor etc. And separate control systems are required for performing desired control and monitoring functions. This results in very large control panels and protection panels and complex wiring. Several operators are required in the control room to supervise the various control and protective panels.

With *microprocessor based combined protection, monitoring and control systems,* the complex tasks are performed automatically. The operator can get necessary information on the VDU (Video Display Unit) of the man-machine interface.

The electromagnetic units, hardwired static relay units and programmable units are used judiciously in the control and protective systems. *For simple functions electromagnetic units will con-*

tinue to be used. For multifunction relays, hardwired or programmable static relays are being preferred. For higher hierarchical levels at substation control rooms, power station control room and load control centres, the Combined Programmable Protection and Monitoring and Control Systems (CPMC) are preferred.

Table 38.1. Evolution of Static Relays and Integrated Protection and Control Systems

Type of Unit System	*Remarks*
Single function relays with : 1 Analogue Circuits 2 Digital circuits	— Performs one or more Protective functions. — Modular concept for subassemblies — Required functional block is assembled to form the relay unit.
Multifunction relays with : 1 Analogue Circuits 2 Digital Circuits	— One or more inputs — The relay unit may be hardwired or programmable.
Hardwired Digital or Analog Static Protective System	— Several relay units required for protection of a machine or power system component are assembled to form one protective system. *e.g.* Generator protection system, has overcurrent, reverse power, under voltage relay units.
Programmable Static Protective System	— It has additional logic circuit and programmable microprocessor.
Integrated Protection Monitoring and Control System. (IPMC)	— It has required functional subsystems such as data acquisition unit, protective unit data transmission unit, control unit. The microprocessor performs several functions.
Also called : Combined Protection Monitoring and Control Systems (CPMC) [Fig. 38.1 (*c*)]	— The protective functions may be segregated (separated) from control functions suitably. *e.g.* protective functions may deal with tripping of breakers whereas the control functions may deal with monitoring data processing and control.

With the developments in semiconductor technology, digital electronics, microprocessor technology and digital control systems fibre-optics data transmission etc. there has been a tremendous leap in the field of a digital static relays. The development of integrated circuits are more reliable and more compact. Furthermore, the microprocessor and digital computers are being increasingly used in power system protection, and control.

The static relays and static protection has grown into a special branch in its own right. This section covers principles and applications of static relays and static protection systems in details.

38.2. STATIC VERSUS ELECTROMAGNETIC RELAYS

The static relays compared to the corresponding electromagnetic relay have many advantages and a few limitations. The choice between an electromagnetic relay and a static relay depends upon

— Technical requirements of characteristics and protective functions.

— Overall cost.

For simple protective functions and for protection of simple low power equipment, electromechanical relays are preferred. Electromechanical units are also be used as components of total predominantly static relay e.g. for auxiliary relay functions, output functions.

For complex protective functions requiring accurate characteristics for various protective functions and for protection of costly, large equipment/machine, static relays are preferred. These may be hard-wired or programmable.

For integrated protection and monitoring systems programmable microprocessor controlled static relays are preferred.

(*a*) Advantages of Static Relays

1. **Low Power Consumption.** Static relays provide less burden on CT's and PT's as compared to conventional relays [Refer Table 38.2 (Also see Sec. 35.4 'Burden'].

In other words, the power consumption in the measuring circuits of Static Relays is generally much lower than for their electromechanical equivalents. The consumption of 1 milliwatt is quite common in static overcurrent relay. Whereas, an equivalent electromechanical relay can have consumption of about 2 watts. Reduced consumption has the following merits :

— CT's and PT's of less VA rating

— The accuracy of CT's and PT's increased.

— Air-gapped CT's can be used.

— Problems arising out of CT saturation are avoided

— Overall reduction in cost of CT's and PT's.

2. **Resetting Time and Overshoots.** By using special circuits, the resetting times and overshoot time can be reduced thereby the selectivity can be improved.

3. **No moving contacts** and associated problems of arcing, contact bounce, erosion, replacement of contacts etc.

4. There is no effect of gravity on operation of a static relays. The relay can be installed in vessels, aircrafts etc.

Table 38.2. Reference Values of Burden of Static Ralays*

Item	*Conditions*	*Burden per phase*
1. Instantaneous Measuring Relay (*a*) Current Relay	Measuring circuit at lowest setting current ; 0.3 A to 20 continuous	7 to 100 mVA
(*b*) Voltage Relay	Measuring circuit at lowest setting voltage : 24 V/48, V/60 V, d.c.	20 mVA
2. Time-lag Over-current Relay	At rated current, given current, setting current 1 to 8 A	0.03 to 0.08 VA
3. Impedance Relay	At rated current, rated voltage (*a*) Current circuit (*b*) Voltage circuit	0.2 to 0.3 VA 0.8 to 0.9 VA
4. Differential Relay for Transformer protection	(*a*) Normal current : 1 A (*b*) Normal current : 5 A	0.02 VA 0.18 VA

5. **Single Relay for Several Functions.** By combining various functional circuits, a single static relay can replace several conventional relays.

For example for motor-protection, a single static relay can provide over current, under voltage, single-phasing, short-circuit protection by incorporating respective functional blocks. This is not possible in electromechanical relays.

6. **Compactness.** Static relay are compact. A single relay performs several functions. A single Microprocessor based system can substitute several independent protection and control relay units. The space required for installing protective relay and control relays etc. is reduced. A single panel can incorporate a protection and control system for several functions.

7. **Superior Characteristic and Accuracy.** The characteristics of static relays are accurate and superior. They can be altered within certain range as per requirement of protection. *e.g.* static distance relay can have narrow rectangular characteristic on R-X plane. Several features can be incorporated depending upon the application requirements. Static relays of superior speed ($\frac{1}{2}$ cycle, 1 cycle) are available.

* As there are wide ranges and applications of static relays, the above mentioned values just for familiarity, not for application guidance.

8. **Transducers.** Several electrical or non-electrical quantities can be converted into electrical quantities and then fed to static relays.

9. **Static Relays can 'think'.** Complex protection schemes employ logic circuits. *Logic means the process of reasoning, induction or deduction.* Suppose, several conditions are imposed on a protective system such that for certain conditions, the relay should operate, and for some other conditions, the relay should remain stable; in such cases logic gates can be adopted.

Digital electronics and Logic circuits are used with multi-input static relays. The relay determines the response depending upon the conditions, of various inputs and the allocated logic.

e.g. Static distance relay can be given additional features of auto-reclosing unit. The relay can determine whether to give reclosing command or not depending upon the impedance measurement, synchronizing check, feature, etc.

10. **Programmable Operation.** The characteristic programmable relays can be altered by changing the programme. 'Programme' means sequential instructions that direct the microprocessor in the relay to perform specific functions.

11. **On-line computation and Functions.** The characteristics and functions of programmable relays can be altered on the basis of on-line computation of various variables.

e.g. which back-up breaker to operate with minimum outage can be decided by prevailing network configuration and on-line real time data.

12. **Interface with SCADA and EMS.** Static protection, control and monitoring system for substations, power stations etc. form a part of SCADA, EMS and AGC Systems which are indespansable in to-days AC Networks. (Ch. 50)

13. **Remote Back-up and Monitoring.** Static relays assisted by power line carrier can be used for remote back up and network monitoring.

In *centrally monitored systems,* the back-up protection is monitored by the digital computer. The switching is carried out in such a sequence that the stability is improved. (Ref. Sec. 43.10)

14. **Repeated Operations Possible.** Static relays can be designed for repeated operations as there are no moving parts in measuring circuits.

15. **Effect of Vibrations and Shocks.** Most of the components in static relays, including the auxiliary relays in the output stage are relatively indifferent to vibrations and shocks. The risk of unwanted tripping is less with static relays as compared to the corresponding electromechanical relays. This aspect makes the static relays suitable for earthquake prone areas, ships vehicles locomotives, aeroplanes etc.

16. **Self-supervision (monitoring) of the Relay.** Complex static relays have a facility of continuous and comprehensive self-monitoring by a special hardware called 'Watchdog' and test software. Any fault which occurs within the relay (*e.g.* failure of a component) are detected at once. Thus, periodic testing of the relay can be minimised.

17. **Simplified testing and servicing.** The static relays are provided with integrated features for self-monitoring, easy testing and servicing. Defective module can be replaced quickly.

18. **Extension of application by adding suitable modules.**

19. **Several functions.** A static protection control and monitoring system can perform several functions such as protection, monitoring, data-acquisition, measurement, memory, indication, data-communication etc.

38.3. LIMITATIONS OF STATIC RELAYS

1. **Auxiliary Voltage Requirement.** This disadvantage is now not of any importance as auxiliary voltage can be obtained from station battery supply and conveniently changed to suit local requirements.

2. **Electrostatic Discharges (ESD).** Semiconductor components are sensitive to electro-static discharges (ESD). Electrostatic charges are developed by rubbing of two insulating components. Some components are more sensitive than others. Even small discharges can damage the components which would normally withstand 100 V. Precautions are necessary in manufacturing of static relays to avoid ESD caused component failures.

3. **Voltage Transients.** The static relays are sensitive to voltage spikes or voltage transients. Such voltage transients are caused by operation of breaker and isolator in the primary circuit of CT's and PT's. Serious over voltage are also caused by breaking of control circuit, relay contacts etc. Such voltage spikes of small duration can damage the semiconductor components and can also cause maloperation of relays. Several relay failures were recorded during 1960 due to the above mentioned cause. The measurements showed that the voltage spikes in secondary circuits can attain an amplitude of 20 kV in rare cases and generally 12 kV.

Special measures are taken in static relays to overcome this difficulty. These include use of filter circuits in relays, screening the cable connected to the relays.

4. **Temperature Dependance of Static Relays.** The characteristics of semiconductor are influenced by ambient temperature. For example, the amplification factor of a transistor, the forward voltage drop of a diode, etc. change with temperature variation. This was a serious limitation of static relays in the beginning. Accurate measurement of relay should not be affected by temperature (–10°C to + 50°C). This difficulty is overcome by the following measures :

— Individual components in circuits are used in such a way that change in characteristic of components does not affect the characteristic of the complete relay.

— Temperature compensation is provided by means of thermistor circuits, digital measuring techniques, etc. Thus modern static relays are designed to suit wide limits of temperatures (–10°C to + 50°C).

5. **Price.** For simple, single function relays the price of static relays is higher than the equivalent electromechanical types. [Fig. 38.1 (*d*)]. For multifunction protection, static relays provide economical solution. The production technology of plug-in type static relays on the panel (Sec. 38.7) permits manufacture of standard relays on large scale. The customer's requirements can be fulfilled quickly by incorporating required relay units on the panel.

6. In electromagnetic relay, the pick-up relays or reset of relays does not affect the relay characteristic since the operation is based on the comparison between operating torques. However, the statics relay characteristic is likely to be affected by the operation of output device.

For simple protective functions, conventional electromechanical relays provide economic and satisfactory choice. For complex protection systems static relays are preferred technically and economically. As static relays perform protective and monitoring functions, the additional cost is justified on the basis of improved system stability, reliability and availability of electric power.

38.4. RELIABILITY AND SECURITY OF STATIC RELAYS

Reliability is defined as the likelyhood of that the device will perform as expected at all times. This includes (1) Security to not operate incorrectly and (2) Dependability to operate correctly when expected.

Security of a Relay or Protection system is the factor of reliability which relates to the degree of certainty that the relay will not operate incorrectly.

Reliability of protective relaying is very important. Electromechanical relays have high reliability, due to (1) precision, manufacture (2) few, reliable components in their construction (3) experience gained in designing manufacturing testing and maintenance Static Relays are in infant stage and have to prove their reliability. As the static relays have several discrete components such as resistors, capacitors, semi-conductors in their construction, reliability depends on reliability of these components and reliability of the total assembly. It is therefore, necessary to choose the components with great care. Each components should be type tested. Care should be taken in connections, soldering etc. The ambient conditions, voltage spike, should also be considered. The use of integrated circuits increases reliability of static relays. *Integrated circuits are much more reliable* *than the equivalent discrete component circuits.* Reliability of components is improved by strict quality control, presoaking the components to improve temperature response presoaking of a relay means, operating the relay under service conditions for certain time with current and voltage connected to it. With this method, bad components and poor joints can be detected.

Self monitoring feature in modern micro-processor based relays ensures indication of failed internal component. Thereby the failed component/circuit can be replaced. This increases the reliability and security of static relays.

38.5. HISTORICAL REVIEW IN BRIEF

- The major break-through in the application of electronics in power system protection occurred in 1928 when carrier current protection system was introduced for the protection of transmission lines. Earlier schemes were with vacuum tubes.
- The protective relays employing the vacuum tubes and gas tubes were not popular due to the short life of tubes, need of heater supply, slow speed, less reliability etc. Their use was mainly in control circuits. Protective relays employing vacuum tubes did not find any commercial success, except for carrier current protection systems.
- Transistors were invented in 1941 which led to a revolution in electronic technology. The development of static relays employing semi-conductor devices such as diodes, transistors, thyristors etc. was started in 1950's.
- The first generation of static relays were with discrete (independent, separately identifiable) component fitted on printed circuit boards (PCB). Relays with PCBs are manufactured even now.
- During the period 1958-1974, many leading manufacturers in the world have conducted research and development in static relays technology. The static relays of second generation employ Integrated Circuits (IC). The ICs may be small scale (SSIC), Medium Scale (MSIC) or large scale (LSIC)
- At present schemes of generator protection, bus-bar protection, transmission line protection etc. employing static relays are being used. These are with IC's and PCBs and are very compact (1980's). The ICs are available for Analogue and Digital Circuits.
- Fibre optic relays (1980's) use fibre optic circuits for conduction of light pulses. Fibre-optic relays and central circuit pilot wiring is gaining commercially success. (1990)
- Earlier generation of static relays (1970s) were with Analogue Circuits. Now Digital circuits are preferred. Such relays are called 'Digital Relays' or 'Numerical Relays'.
- Development of digital Electronics and Microprocessor (1980s) has resulted in programmable multi-function systems. The functions include measurement, data transmission, protection and control. Microprocessor controlled relays have become popular. (1990's)
- **Communication.** During 1980s, power system data communication systems with (1) carrier communication (2) Microwave radio communication (3) Telephone communication (4) FASIMILE transmission (5) Satellite communication systems, have been introduced for protection, monitoring and control.

38.6. RECENT DEVELOPMENT OF STATIC RELAYS

The present trends in static relays indicate the following aspects :

- *Miniaturization.* Due to change-over from discrete components to integrated circuits, the measuring parts of static relays are compact. The size of the complete relaying system will be influenced by the size of the transformers.
- *Increased reliability and reduced price.* Static relays with ICs are cheaper than these with discrete components.
- Use of digital techniques for measurements, instead of analogue techniques, used earlier. Thereby the tolerance of individual components will not influence measurement.

- Use of new type of instrument transformers instead of conventional CT's and PT's in ultra-high voltage networks. Development of optoelectric components for protection is in progress. We can expect the development of static relays to suit such devices.
- Increasing use of digital computers and microprocessors in power system protection. A closer co-operation of static relays and Energy Management Systems, Scada Systems etc. is in the offing.
- Programmable Relays, instead of Fixed-wired Relays. This gives 'flexibility' to the protection system.
- Combined Programmable Protection, Monitoring and Control Systems. (CPMC) have been introduced for Protection and Control of EHV-Substation.
- Use of fibre-optic cables in pilot wire differential protection.
- Ultra high speed directional wave relay (5ms) for protection of UHV AC lines and EHV-AC lines.
- Power system simulator for realistic testing of static protection systems.
- Protection and control system for HVDC-Substations.

Table 38.3
Electromagnetic Versus Static Relays

Function	*Conventional Relay*	*Static Relay*	
		Without Thyristor	*With Thyristor*
1. Input	1-3 W	10 mW	20 mW
2. Switching capacity	30 W	10 W	100 W
3. Power gain	8-32	1000	500
4. Continuous current rating	5 A	1 A	1 A
5. Time	10 m sec	20 sec	50 sec
6. Effect of vibration	Bearing affected	No effect	No effect
7. Ambient temperature range	No effect 5 to 70° C	Needs compensation	Needs compensation – 20°C to 100°C
8. Operations	Above 10^6	No limit	No limit
9. Effect of pollution	Yes	No	No
10. Testing	Easier	Difficult	Difficult

38.7. PRESENT TRENDS IN PROTECTION AND CONTROL TECHNOLOGY (1997)

The trends have been from *simple electromechanical relays, to Microprocessor-based Digital Relays* and finally Combined (Integrated) Protection. Monitoring and Control Systems for substations, generating stations and load control centres.

These trends have followed the advances in digital electronics, digital computer technology, microprocessor technology etc. and are listed in Table 38.4. The details have been covered in subsequent chapters.

The application of electromechanical, static, digital static, microprocessor based relays depends upon *complexity of protective functions.* For simpler single functions, electromechanical relays may be preferred. For complex, multi-functions microprocessor based relays may be preferred Ref. Fig. 38.3.

Table 38.4. Historical Trends in the Protection and Control Technology

Years	*Product description*	*Remarks*
1880—1940	Electromechanical relays of various types for : — Protective functions — Control functions	Used even today for simpler protection functions and simpler control functions.
1940—1960	Static Relays with vacuum tubes for carrier differential protection and microwave protection of transmission lines	Lateron replaced by static relays with semiconductors.
1960—1970	Static Relays (Analog) for protection of motors, generators, transformers, busbars transmission lines etc.	Analog relays may have a PCB and IC.
1965—70	Digital static relays	Used A/D conversion and digital Electronics Techniques IC, LSIC's used.
1968—75	Digital computer based static protection systems used for transmission systems for main and backup protection.	On-line digital computer used for protection type prodar 70 installed by westinghouse USA (Ref. Sec. 46.15)
	Proved costly for simpler protective functions.	Used in Generating stations, substations control centres etc. (Ref. sec. 46.4)
	Digital computer based systems for — Data Acquisition — Data monitoring — Data transmission — Data processing — Data display.	Integral part of Network control (Ref. Sec. 50.4).
1968—75	Various types of Digital computers installed in generating station control room, substation control room and Load control centres for Network monitoring and Network Automation.	— Large computers for load control centres. — Medium computers for Generating stations and substations. — Minicomputers for small substations. (Ref. Sec. 46.9)
1975—85	Microprocessors introduced for power system control and power system protection *Proved cost effective and advantageous for protective relays and control.*	Each individual protective system or control system can have its own microprocessor. Becoming increasingly popular. Ref. Ch. 43.B
1985—95	Combined (Integrated) Protection, Control and Monitoring systems based on Digital Computers, Microprocessors.	— For integrated substation control and protection — For integrated generating station protection and control. — For system control from load control centres.
1985—95	Introduction of SCADA systems AGC Systems EMS system etc.	Supervisory control and Data Acquisition systems (SCADA) are applied to AC Network. The protection and control functions are sub-divided at various levels in — Load control centre — Generating station control room. — Substation control room. — Major load centres etc.

Ref. Fig. 38.1 (*d*) which gives the trends over the years.

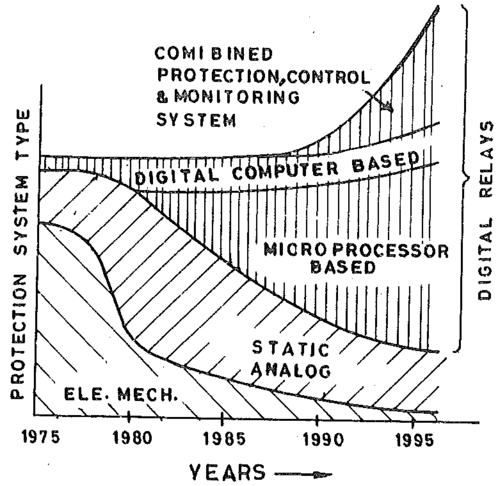


Fig. 38.1 (*d*). Application trends of the various alternative types of protective relays over the years.

(In 1975 the Static Relays were used only for complex functions such as a generator protection, EHV-line protection etc. Today Static Relays have replaced electromechanical relays in al-

Electromechanical Relays. These are ideally suitable for simple protective functions of individual loads. They are least costly in such applications. However for complex protective systems such as protection of transmission lines, protection of generators, protection of large motors etc. electromechanical relays are technically not preferred Several relays are necessary in the protection system the cost of protection with electromechanical relays increases rapidly with the complexity of protection (in terms of speed, characteristic number of functions etc.)

Static Relays (Analog). These are suitable for more complex functions and are preferred for almost all protective systems. With the use of printed circuit boards (PCB) and single chip IC's the cost of static relays has reduced rapidly and they are used for a wide range of applications.

Digital Static Relays. The logic circuits and digital electronics are used in relay circuits involving several functions. Such relays are preferred for complex protective systems. The relays may have PCB or IC having fixed circuit.

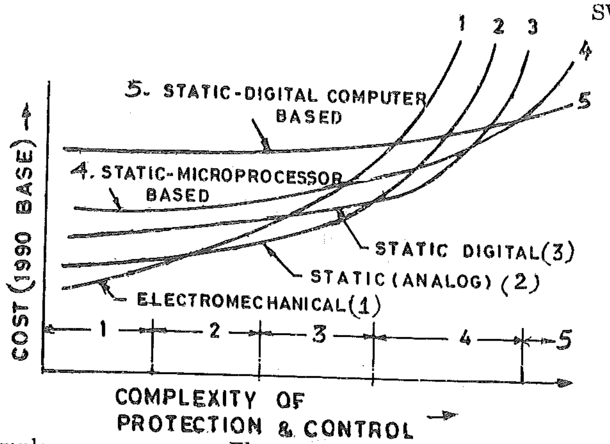
Programmable Relays with Microprocessors. These were developed during 1975-95 and have become *extremely popular* over a very wide range of applications. The microprocessor is provided within the relay. The relay can therefore perform logical functions. *The relays may be with fixed programme or variable programme. Cost of microprocessor based relays is much less than the earlier computer based protective relays.*

Digital Computer based Protective System. These were developed during 1968 in USA. However they are costly and can be justified for very complex multifunction EMS and SCADA systems. They are not preferred for individual protection systems.

Combined Protection, Monitoring and Control Systems (CPMC). These are being used for substation protection and protection in generating stations, protection of HVDC systems etc. They are generally microprocessor based. They simplify the entire protection and control system and they prove less costly for more complex and remote unattended power stations/substations.

Fig. 38.1 (*e*) and 38.1 (*f*) illustrate the applications and cost aspects of the above types of protection devices.

Combination of Static and Electromechanical Relays. At present both static and electromagnetic units are used in protection systems. 'All-or-nothing' relays are generally electromechanical type and measuring relays are either static or electromechanical. For simple



1. Least complex	: Electro-mechanical relays
2. Slightly complex	: Static (analogue)
3. More complex	: Static (digital)
4. Very complex	: Static-Microprocessor based
5. Extremely complex	: Static-Digital Computer Based.

Fig. 38.1 (*e*). Preference of type of relay system with reference to *cost* and *complexity*.

protective measuring functions, electromechanical relays are preferred. For complex protective measuring functions, static relays are preferred. Hence, the electromechanical and static relays are equally important. Electromechanical relays are not obsolete.

38.8. MODULAR CONCEPT, BUILDING-BLOCK PRINCIPLE USED IN PREDOMINANTLY STATIC PROTECTION SYSTEMS

Modern protective measuring relays, all-or-nothing relays and other auxiliary devices are generally of plug-in-type. The required modules are plugged into terminal base. The terminal base fits into the switchboard cases and rackmounted frames. The required plug-in-devices are selected to form the required protective and control systems. *e.g.* app. 50 cm × 20 cm panel space can accommodate upto twenty relay modules with individual targets and 120 contacts. With plug-in type modules, the time required for screwing is avoided. The wiring is also minimised. *The required electromechanical or static relay modules and other auxiliary devices are plugged in to form the protective and control system.*

38.9. STATIC RELAY FUNCTIONAL CIRCUITS AND INDEX OF FUNCTIONS

The various functional requirements for measuring units, all-or-nothing units, auxiliary units and components are defined, standardised and each unit given certain index number. The index of functions consists of over 300 identified and standard functions.

The *predominantly static relay* is formed by combining required protective and auxiliary relay functions with one or more static relay unit.

The basis protective functions *required for protection of Generators, Motors, Transformers Lines, busbars etc. are identical with those studied in earlier chapters. Only the range and characteristics differ with each application, e.g.* consider overcurrent protective function which is used in generator protection, motor protection, transformer protection. The *overcurrent protection* may be further subclassified into :

— Instantaneous overcurrent
— Inverse time overcurrent
— Directional overcurrent
— Definite time overcurrent
— Under current
— Phase fault, Ground fault functions.

The basic overcurrent functional circuit or unit is used in respective static protection system for achieving overcurrent function. In static relays a large number of protective functions can be combined in one relay unit. In static protective systems, several protective relay units can be combined on one protection panel.

The principles of basic protective functions, *viz.* overcurrent, differential, distance etc. and the basic principles of protective zones main and back-up protection, desirable aspects of protective relays with respect to speed, accuracy, selectivity, discrimination sensitivity, reliability, adequateness, characteristic CT and VT connections etc. described in Ch. 25 to 37 apply to static protection systems. However, measurements in static relays is performed by electronic circuit and not by an electromechanical unit.

The standard terms and definitions (Sec. 25.8) have been evolved based on electromechanical relays and their protective systems. These terms are generally applicable to predominantly static relays with certain restructuring wherever necessary. *Terms and definitions used with Digital Computers and Microprocessor (Sec. 46.2) are applicable in the terminologies for Microprocessor based protective and control relays.*

The following sections and Chapters have a reference to predominantly static relays.

38.10. TYPES OF MEASURING AND ALL-OR-NOTHING RELAY UNITS (Ref. Sec. 25.8.3)

1. **Measuring Relay.** The relay which responds to an electrical quantity (or one of its parameters the name of which characteristics of the relay) and the response of the relay depends upon the measurement of the characteristics quantity and the response characteristics of the relay.

2. **All-or-nothing Relays and Auxiliary Relays.** All-or-nothing relay is an electrical relay which is intended to be energized by a quantity, whose value is either

— higher than that at which is picks up
— or, lower than that at which it drops out.

Note. The adjective 'All-or-nothing' can be deleted when no ambiguity will result. Auxiliary relays, latching and time delay relays fall into the category of All-or-nothing relays.

3. **Latching Relay (Bistable Relay).** It is an electrical relay which having responded to an input energizing quantity (or characteristic quantity) and having switched, remains in that condition after that quantity has been removed.

The position of a bistable relay can be controlled by two input circuits (*A* and *B*) or by two methods of connections of one input circuit (*A*)

— The *A* condition is that condition which corresponds to the energized condition related to *A* input circuit.
— *B* condition corresponds to energized condition of *B* input circuit.

4. **Monostable Relay (Self-reset relay).** A relay which having responded (to an input energizing quantity or characteristic quantity) and having changed its condition returns to its previous condition when the quantity is removed.

5. **Timing Relay or Time Delay Relay.** A *time-delay relay* that introduces a fixed or set-time delay into the operation of associated function. *Non-specified-time relay* has no accurate time.

6. **Static Relay.** An electrical relay in which the response is developed by electronic, magnetic, optical or other components without mechanical motion.

Note. A relay which is composed of both static and electromechanical units and which is designed to achieve the response by means of static units is also called a static relay. In static relays the measuring relays are static. The all-or-nothing relays are either static or electromechanical.

7. **Starting Relay or Starting Unit (Element).** The element (unit) or a protection system which responds to faults or abnormal service conditions and initiates operation of other elements (units) of protection system.

8. **Polarisation.** A term applied to input that provides reference for establishing the direction of system phenomena (such as direction of real power, direction of reactive power, direction of fault, direction of disturbance).

9. **Biased (Restraint) Static Relay.** Bias (restraint) means the action of input quantity which when present results in increase in the threshold value of another input quantity or otherwise limits the operation of the relay. Biased Relay is a relay in which the operating value is modified by means of additional electronic circuit which provides restraining rendency.

10. **Blocking Element (unit or relay).** An element (unit or relay) of a protection which under certain conditions limits or prevents the operation of other elements.

11. **Programme.** A sequential instructions that direct a microprocessor or computer to perform desired arithmetic and logical operations to perform specific tasks. Programmes form the software.

Programmable Relay : Flexible Relay, Microprocessor Based Relay.

A relay which responds to electrical quantities in accordance with the programme.

A programmable relay (or system) has a microprocessor or a microcomputer its functional system. The programmable relay (system) performs protection functions/control functions/data transmission functions/memory functions/self monitoring functions etc. by means of digital measuring techniques, programmable logic. The type of characteristic (*e.g.* inverse, very inverse, extremely inverse, definite time) can be selected directly of the relay in accordance with the changes in the network.

12. **Real Time (On line).** The actual time during which the relay/protective systems is in the state such that it can respond in accordance with the programme. On line protective and control system is a programmable system which takes into account the actual quantities on the line in real time.

38.11. ANALOGUE AND DIGITAL SUB-SYSTEMS IN PROTECTIVE RELAYING

The hardware used in the protective relaying system can be divided in the following three major classes :

(1) Analogue (2) Digital (3) Hybrid

All the three types of hardware are now commonly encountered in the power system protection, monitoring, control and also in various branches of power system engineering. Whereas during 1960's analogue and digital computation hardware was not introduced in stand-alone functional assemblies, the situation has changed rapidly during 1970's and 80's. The development of Large Scale Integrated Circuits (LSI) technology has resulted in development of both *Analogue and Digital* functional devices called *'Microchips'.* (Ref. Sec. 38.9)

The microchips (either Analogue or Digital) are functionally powerful (can perform several functions) and relatively cheap (as compared with earlier PCB circuits) (Ref. Sec. 38.9)

The protection/monitoring/control system has several functional systems (modules)

The functional modules can be either analogue or digital and in the form of :

Table 38.5. Forms of Functional Modules

— Discrete components connected by hardwire**
— Printed Circuit Board (PCB)**
— Integrated Circuits (ICs)**
— Large Scale Integrated Circuits (LSIs)**
— Microprocessor-based circuits*
— Digital computer based circuits*.

38.12. ANALOGUE PROTECTION SYSTEMS

In the engineering practice, analogue electronic circuits are used universally. These may be in form of PCB's or IC's. The required relay characteristics with certain variables (*e.g.* I and t for over-

*These are Digital type fixed programme or may be programmable.
** These are either analog or digital.

current relay) are represented by equations. The analogue circuits are formed by resistance capacitance, inductances, and protective features are added by using comparators. The analogues quantities are compared in comparators and the comparator distinguishes between the healthy and abnormal condition in the protected circuit. The analogue circuits can be used for solution of differential equations, for integrating current/voltage, for scating, for amplifying, for summing, for comparing and for obtaining more complex characteristics. Table 38.6 gives summary of important analogue circuits used in protective relays.

Table 38.6. Standard Analogue Electronic Circuits used in Static Relays

Analogue circuit	*Remarks*	*Reference*
1. Operational Amplifiers	— Basic element in analogue computation.	Sec. 38.21
	— Represented by a triangle.	Fig. 38.29
	— Used in circuits for addition, subtraction, integration, differentiation, and other combinations.	
	— Available in the form of IC, L.S.C.	Table 38.3
	— Available in very wide range of specs.	
	— Has limitations.	Table 38.13
2. Inverting Amplifiers	$V_0 = \frac{R_2}{R_1} V_1$	Sec. 38.24
3. Analogue Addition Summer.	$V_0 = -(V_1 + V_2)$	Sec. 38.24
4. Analogue subtraction (subtractor)	$V_0 = V_2 - V_1$	Sec. 38.24
5. Analogue Integrator	$V_0 = \frac{1}{RC}\int V_s\,dt$	Sec. 38.24
6. Analogue Differentiator	$V_0 = -RC\frac{dV_s}{dt}$	Sec. 38.24
7. Analogue Level detector.	$V_s = \pm V_\alpha$	Sec. 38.24
8. Analogue Comparator	$V_s > V_\alpha$ output V_0 positive $V_s < V_\alpha$ output V_0 negative Alternatively Output V_0, $V_0 = O$ for $(V_2 - V_1)$ Positive $V_0 = V_\alpha$ for $(V_2 - V_1)$ Negative.	Sec. 38.24
9. Function Generator	Generator certain well defined forms of functions *e.g.* steps, ramps, square wave triangular wave, sine wave. Standard function generators are commercially available.	
10. Multifunction convertors.	Several standard combinations of available commercially which provide a range of non-linear analogue functions *e.g.* a typical convertor may provide : Multiplication, division, square, square root, exponential, roots, sines, cosine, $\tan^{-1}(y/x)$, $\sqrt{x^2+y^2}$, $\log x$ etc.	
11. Analogue computer.	It comprises several operational amplifiers circuits such as summer, inverter etc. The analogue computers are used for power system studies and in real time computing.	
12. Digital to Analogue Converters (DAC)	Gives Analogue output V_0 proportional to the digital input (V_1).	
13. Analogue to Digital Convertor (DAC).	Gives Digital output V_0 proportional to analogue input V_s.	Sec. 31.25
14. Analogue Multiplexers.	Used for converting a number of Analogue signals to a single ADC.	
15. Hybrid circuits	By use of ADC and DAC the analogue and digital circuits are combined to get Hyb.	

38.13. LIMITATIONS OF ANALOGUE SYSTEMS

— Analogue computation has lesser accuracy. The accuracy is limited by resolution with which the chosen analogue quantity (*e.g.* current) can be measured. Analogue quantities are, in principle, continuous and the limits of resolution are physical effects such as wire-to-wire spacing of potentiometers, random circuit noise etc.

— Operational amplifier have following limitations :

1. Voltage gain falls and phase shift is produced between input and output signals for frequencies beyond the range.
2. The transient response to step functions in sluggish.
3. Output impedance is low.
4. With feedback, operational instability may be introduced.
5. Logic operations are difficult to be obtained.

— Digital and *programmable operations* are not possible. This presents a seniors limitation in complex protective functions. Hence, analogue protective relays are used for less complex functions.

— *Digital techniques* are being used increasingly and are replacing analogue techniques for many protective functions and this trend with continue.

38.14. DIGITAL AND PROGRAMMABLE ELECTRONIC STATIC RELAYS

Digital electronic circuits process the information by processing descrete electrical signals in digital form. They can perform simple logic and arithmetic operations and can therefore be used to construct the basis functional circuits required for protective relaying system. The digital electronic circuits can be used to hold and store discrete information by means of 'memory'. The ability to store the information or data and to process the data by logical and arithmatical means is the inherent feature of digital data processing systems including microprocessor and digital computers.

The protective relaying functions require sequential operations depending upon information being processed. The digital protective relaying has ability to determine the sequence of operations which are performed on the basis of the information or data being processed. A digital system can be classified by the wave in which the sequence of operation is to be implemented.

Presently three forms of digital systems have become commercial successful :

1. Hardwired logic is used extensively for performing combination and sequential logic operations.

2. Microprocessor

3. Very large scale Integrated devices (VLSI)

38.15. HARDWIRE DIGITAL SYSTEMS

A digital system is called *hard-wired* if the sequence of operation is governed by physical interconnections of the digital processing elements by means of solid conducting paths (hard-wires). For example in a hard-wired logic system, physical interconnections of elements, determine the route by which the data flow between processing elements. The physical interconnection (hard-wired) determine the sequence or processing operations performed on the data. Thus the hard-wired digital protection and control system has fixed sequence of digital computation process and fixed sequence of operations.

This type of system is designed for specific protective or control function and is therefore inflexible. If the processing function has changed and the sequence process of logical operation is to be charged the processing elements and their interconnections (wiring) also need to be altered.

38.16. PROGRAMMABLE DIGITAL PROTECTIVE AND CONTROL SYSTEMS

A digital protective and control system is called 'Programmable' if the data processing function in the systems can follow a 'Programme' *i.e.* the sequential instructions to perform specific tasks (Sec. 43.28)

Programmable Digital system incorporates a general purpose processing element (Microprocessor or Digital computer) to which a programme (instructions in particular required-fashion) are fed. The programme has a purpose to implement specific functions in predetermined way.

The coded instructions are normally stored in the memory part of the system and the program forms an integral part of the system.

The ability to define the digital functions by programming gives a significant 'flexibility' into the system. It also enables an identical programmable hardware to be used for several different applications by using appropriate programmes.

38.17. FORMS OF DIGITAL ELECTRONIC CIRCUITS

1. For less complex functions, hard-wired digital logic circuits are used extensively to perform several logical functions. The integrated circuits may be called :

— Small Scale Integrated Circuits (SSTC)

— Medium Scale Integrated Circuits (MSIC)

— Large Scale Integrated Circuits (LSI)

— Very Large Scale Integrated Circuits (VLSI)

2. For complex functions where flexibility is required programmable devices are used.

The programmes may be of following types :

— Microprocessor based for complex functions

— Digital computer based for very complex functions.

The trend is toward increasing use of microprocessor based protection systems with each in dividual protected system.

38.18. INTEGRATION A CONTROL AND PROTECTION FOR HIGH VOLTAGE AC SUBSTATION

The modern AC Networks are formed by interconnections two or more independently controlled AC Networks (Areas). The hierarchical levels of control include (1) National Load control centre (2) Regional load control Centres (3) Power Station Control Rooms (4) Substation Control Rooms (Sec. 46.1, 50.4). Several supervisory, control and protection functions are performed from substation control room.

Before 1985, the protective functions were segregated (separated) from control functions, with traditional electromechanical relays and earlier generation of hard-wired static relays, the functions of protection systems were limited to (1) Sensing faults and abnormal conditions (2) Giving alarm (3) Tripping circuit-breakers (4) Autoreclosing of Circuit-breakers. *The substation supervisory functions and control functions were independent of the above protective functions.*

With the development of Programmable Digital Systems *i.e.* Microprocessor Based Systems, the entire supervisory functions, control functions, protective functions can be combined (integrated). The microprocessor based or Microcomputer based Integrated or Combined Protection, Monitoring and Control Systems (CPMC) have been introduced for EHV Substation and HVDC Substation during 1985-90 and are capable of performing the following functions.

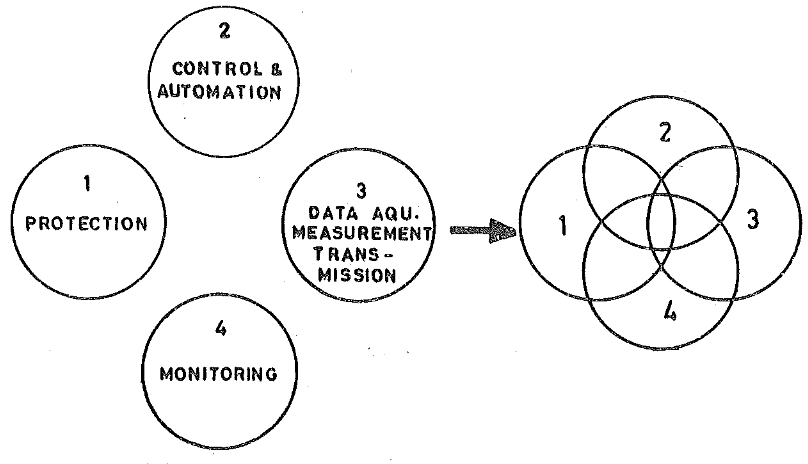


Fig. 38.1 (*f*) Concept of combined Protection, Monitoring and Control System (CPMC) with modern microprocessor-based Digital Relays.

Table 38.7. Functions of Combined Protection, Monitoring and Control (CPML) in EHV-AC Substations

Protective Functions	Busbar protection, Transformer protection, Transmission line protection.
Automatic functions	Synchronizing. Load switching, Sequential operations Tapchanging and voltage control. Load Shedding System restoration
Supervision and Monitoring	Data collection Data logging Fault annunciation Sequential event recording Measurements Disturbance recording Remote control
Interlevel communications.	Communication between two levels *e.g.* control centre and sub-station control room.
Manmachine Interface	Display, instructions etc.

Construction Principle. Most of the functions are performed by the substation CPMC system by means of Microprocessor or microcomputer in accordance with the stored Software (programme). The software in modularised to facilitate incorporation of new functions and to simplify future extension. Building block principle is used. The total CPMC system is tailor-made with required plug-in modules inserted on a standard racks. Combined protection Control and Monitoring System prove economical for complex protective tasks such as those for EHV-AC substations and HVDC substations.

Summary

In static relays the measurement is performed by static circuits. The static relays have following types :

(1) Analogue relays (2) Digital Relays. The static relays are assembled by using *Printed Circuit Boards (PCB)* or Integrated Circuits (IC's). Earlier relays were fixed wire relays having certain functional circuits.

The recent generation of static relays are 'Programmable Relays'. Programmable static relays are *'flexible'*. Programmable static relays include 'Microprocessors' or 'digital' computers in their circuits. Most recent advances include Combined Protection Monitoring Control Systems incorporating microprocessors or microcomputers.

With the developments in *digital techniques and microprocessors,* the static relays with microprocessors have become commercially acceptable. The static relays are preferred for almost all protective functions and the use of electromechanical relays is now rapidly reducing to very simple protective functions and auxiliary relays.

38-B

Introduction to Analogue and Digital Static Relays

Semi-conducting Material — Semi-conducting Devices — Diode — Transistor — Thyristor — Zener Diode — Thermistors — Logic Circuits — Digital Systems — Analogue Systems — Operational Amplifier and its Applications — Analogue/Digital Conversion — Auxiliary Voltage Supplies — Smoothing Circuits — Use of Zener — Timer Circuit — Transducers — Static Directional Units — Logic Circuits — Negative Sequence Circuit — Summary

Section 1. SOLID STATE DEVICES

38.19. SEMICONDUCTING MATERIALS

The common semiconducting materials are germanium and silicon. The resistivity of semiconductors lies between that of insulators and good conductors. The electrical resistivity of semiconductors decreases with temperature. Both germanium and silicon belong to the 4th group of periodic table, thereby they exhibit inertness. These materials have covalent bonds amongst their atoms.

If germanium or silicon crystals contain no impurities, the only current carries present are those produced by the thermal breakdown of the covalent bonds.

They are called intrinsic semiconductors. In general however the germanium crystals contain some trivalent (such as iridium) and some pentavalent (such as Arsenic) impurities of the materials. The formation of covalent bonds with a pentavalent impurity still leaves an excess electron in the outermost orbit of the atom thereby making the material behave as if it is an *n-type material.* It means that the excess electron or negative change is available for conduction. Silicon is used in semiconductor devices now.

In a similar way an addition of a trivalent impurity makes the material behave as if it is *P-type.* This is because there are only three electrons in the outermost orbit of the impurity atom which has to form a bond with the 4 electrons in the outermost orbit of the atom of the material, thereby giving a deficiency (hole) of an electron for stable covalent bond.

As a result pentavalent impurity in the semiconducting material makes it behave negatively (surplus electrons) and trivalent impurity makes the materials positively (surplus holes or unfilled electrons). For *n*-type materials, electrons are called major carriers holes being minor carriers. For *p*-type materials it is *vice-versa.* Semiconducting materials added with such impurities are called Extrinsic semiconductors.

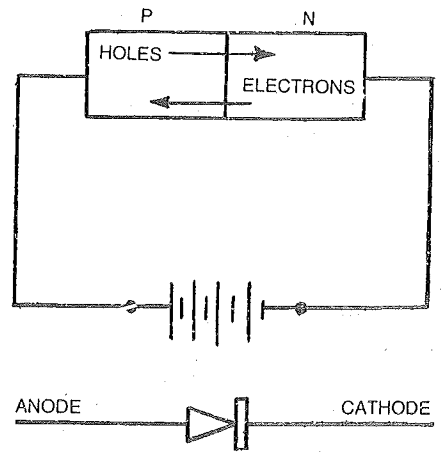


Fig. 38.2. Forward Bias of a *p-n* junction.

P.N. Junction

When there is no external connection made to *p-n* junction there is tendency due to diffusion for the electron of the *n*-region to cross in the *p*-region and *vice-versa.* This creates a potential barrier across the junction as if an external source of e.m.f. is connected.

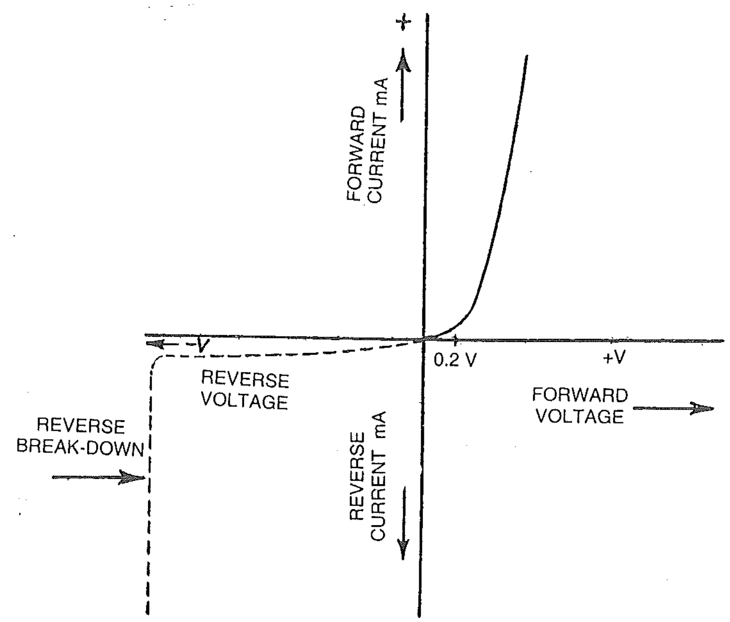


Fig. 38.3. Current voltage characteristic of *p-n* junction Diode.

The majority carriers are now able to cross the junction constituting considerable currents. The relation between current and voltage is shown in Fig. 38.3 *p-n* junction has rectifying characteristic.

When alternating voltage is applied to the *p-n* junction, large current flows for half cycles during which *P* is positive and *N* negative.

38.20. SOLID-STATE DEVICES : (BRIEF INTRODUCTION)

Several solid-state devices have been developed during the last thirty five years and several new are being developed. A brief introduction to solid-state devices is given here for the sake of familiarity.

38.20.1. Semiconductor Diode

A junction between *n*-type and *p*-type semiconducting materials is called *p-n* junction. Diode consists of a *p-n* junction and has two terminals. There are several types of diodes. The manufacturing methods include grown junction method, alloy junction method, diffused-junction method, combination method. Diodes are rated for peak inverse voltage (p.i.v.), *i.e.* maximum voltage between anode and cathode which the diode can withstand in reverse direction. While employing diode in a.c. circuits, the peak voltage of alternating voltage should not exceed peak inverse voltage of diode. Diode is used for rectification. Diode offers low resistance to current in forward direction and high resistance in reverse direction. The parameters of a diode include the p.i.v. maximum power dissipation, maximum voltage and current, operating temperature and storage temperature, capacitance, recovery time, maximum forward and reverse current, time of application of voltage surge, etc. Point contact diodes have high peak inverse voltage, high reverse resistance. They are used in high frequency and fast switching applications. Current limiting diodes allow constant current for a wide range of voltage across them. They are used in bias circuits, differential amplifiers, ramp and stair generators, over-current protection within the circuits, etc. Planer diodes are amongst the integrated circuits. They have high reliability, reduced capacitance stable performance, high switching speeds. Zener diodes have constant voltage across them for wide range of reverse current. They are used for voltage stabilization and voltage regulating circuits.

PN junction diodes can conduct only in one direction, *i.e.* in the direction of the arrow.

Semi-conductor Devices for Static Relays.

As regards, diodes and transistors, only silicon type are used today. Germanium is no more used due to poor quality such as high temperature dependance. Avalanche type diodes are used in circuits exposed to voltage transients. Avalanche diodes have better withstand against transient overvoltages compared to other types. Regulating diodes (Zener diodes, current regulating diodes) are used on static relays mainly to obtain stable reference voltage. In static relays circuits voltage stability tends to be the best at 5-6 volts with very low temperature coefficient and hence zener diodes with this zener voltage rating are widely used. Current regulating diodes are also called upon to protect the sensitive components from voltage and current transients. Uni-junction transistors are mainly used in time circuits as voltage level sensor organs where they have proved to be stable and have low temperature dependance. Thyristors are used in output stage in series with trip coil or tripping relay. A sudden rise in anode-cathode voltage can unduly trigger the thyristor. Hence triggering of transistor due to over-voltage transient should be prevented.

38.20.2. (B) Zener-Diodes (Voltage Regulating Diodes)

Zener diode is used for voltage stabilization.

Zener diodes have been developed in range of from a few volts to several hundred volts and for power-handling ability of over 100 Watts.

Some reverse biased junction diodes exhibit breakdown at a very low reverse voltage (about 5 volts) due to spontaneous pairs within the junction region from inner electron shells.

Zener diode can operate in reverse breakdown mode continuously without damage. Fig. 38.4 illustrates the characteristic of a zener diode. Under reverse breakdown condition, for a wide range of current the voltage across the zener diode remains constant. This property is used in voltage regulator circuits.

Zener diodes are silicon diodes, having low reverse voltage and reverse current being very small, at a certain reverse voltage however the current increases very rapidly and is limited by external impedance. The voltage across the zener diode remains fairly constant over a wide range of reverse currents. Hence, the voltage across the zener diode is held constant and the zener diode can be used for stabilizing the voltage. The reverse voltage at which the suddenly increase current occurs is called Zener voltage or breakdown voltage. No damage is done by operating zener diode in reverse current condition upto certain limit. Zener diodes are available with zener voltages from 3V to several hundred volts 50 volts being quite common.

The voltage of Zener diode changes with temperature. Zener diodes below zener voltage above about 5 V (called avalanche diodes) have positive temperature coefficient. Below this value the Zener diodes (called field effects diodes) have negative temperature coefficient. A combination of forward connected diodes and reverse connected zener diodes is used to overcome temperature effects.

Zener diodes can be connected in suitable series circuit along with volt-

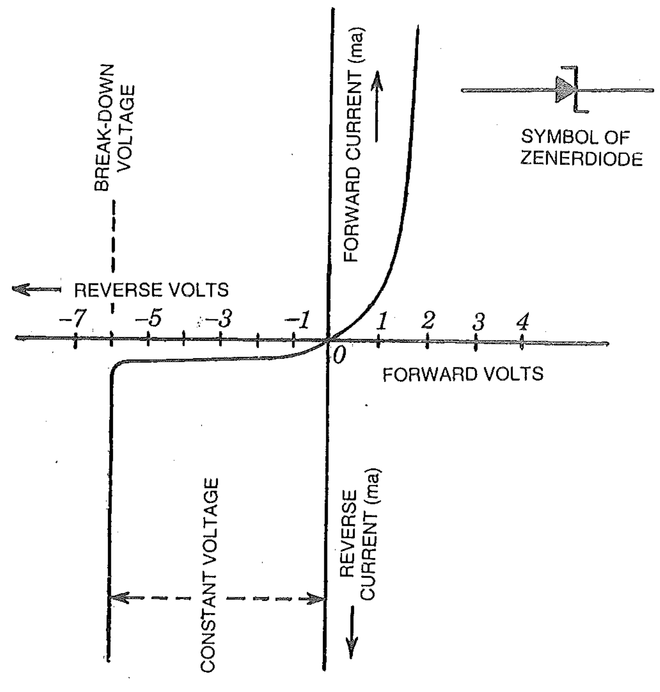


Fig. 38.4. Characteristic of Zener diode.

age grading parallel resistors for surge suppression.

38.20.2. (C) Junction Transistor (Bipolar Transistor)

Transistors are used in amplifiers, level detectors, switching circuits.

A junction transistor has two junctions and can be either *PNP* or *NPN* transistor as shown in Fig. 38.5. In *PNP* transistor a *N*-type layer is sandwiched between two *P*-type layers [Fig. 38.5 (*a*)].

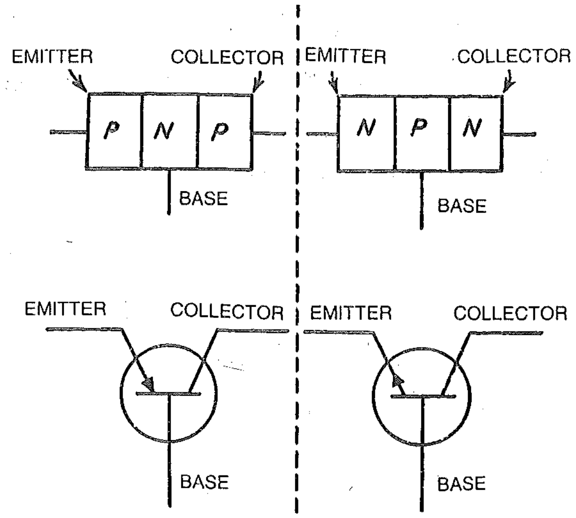


Fig. 38.5 *PNP* and *NPN* Transistors.

In NPN transistor a *p*-type layer is sandwiched, between two *N*-type layers [Fig. 38.5 (*b*)].

Fig. 38.6 (*a* and *b*) illustrates the circuit, symbol and Fig. 38.7 represents the characteristic of a FET. There are several other combinations of connections. When drain voltage is increased, the drain current increases. The slope of $l_N - V_{DC}V_{DC}$ depends upon V_{GS} (Gate to source voltage).

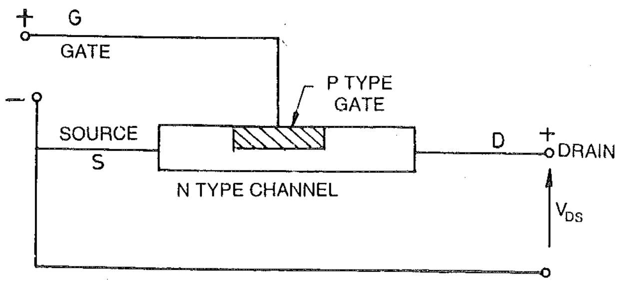
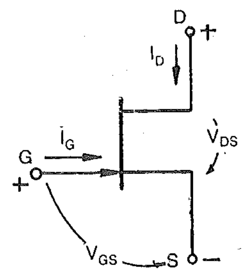


Fig. 38.6 (*a*) Structure of FET.



S = Source Terminal
G = Gate Terminal
D = Drain Terminal

Fig. 38.6 Symbol of FET (Field Effect Transistor).

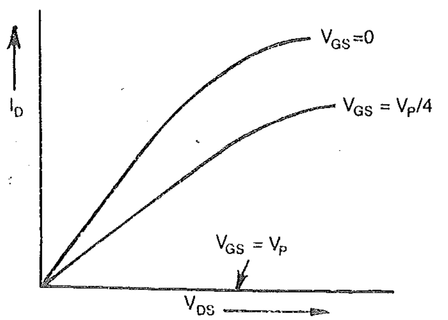


Fig. 38.7. Characteristics of FET.

38.20.3. PNPN Devices and Thyristor Tripping Circuit

PNPN devices consist of four regions arranged as shown in Fig. 38.8. We will briefly discuss about silicon-controlled rectifier Silicon-controlled rectifier has two stable states, one in which the resistance is very low (the conducting state) and the other in which the resistance is very high (non-conducting state). The device can be switched from non-conducting to conducting state very rapidly, and very little power is required to bring about this change. Thus PNPN device exhibits a property similar to that of thyratron but is far more efficient. The device is mainly used for switching and power control *e.g.* controlled rectifier. In thyristor (SCR) a brief signal (positive-charges or holes) into the base *P*-gate causes current to flow. The action is self-sustaining and even if the gate current is removed, the anode current continues to flow. In other words the thyristor is on. A reverse signal to the gate (negative) can make the thyristor off. Or if the circuit is interrupted by the auxiliary switch of the circuit breaker, the original non-conducting state is reached.

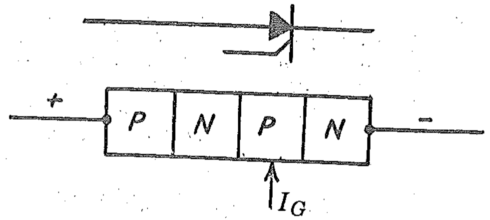


Fig. 38.8. Schematic diagram of *PNPN*, *P*-gate type.

Thyristor (Silicon Controlled Rectifier) is employed in the output stage of static relays as illustrated in Fig. 38.9. The measuring circuit of relay sends a pulse to gate of thyristor when threshold condition is reached. The thyristor triggers and the current from battery flows through trip coil of the circuit breaker. The circuit breaker opens and the auxiliary switch also open as it is interlocked with the circuit breaker and thereby the thyristor is turned off.

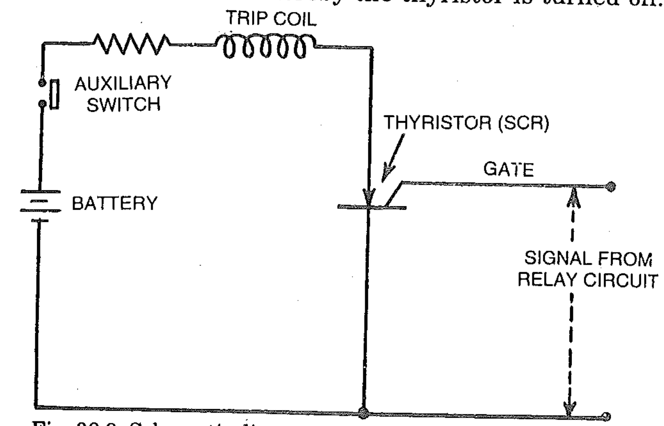


Fig. 38.9. Schematic diagram of thyristor tripping circuit.

There are several types of thyristors such as :

(1) Reverse blocking thyristor (2) Bidirectional thyristor (3) Turn off Thyristor (4) *P*-Gate Thyristor, etc. The following discussion pertains to *P*-gate thyristor only.

1. Application of positive voltage to gate with respect to cathode terminal.

2. Setting up a displacement current in *P*-type region, by means of a pulse-positive with respect to cathode, to the gate. The second method is used in the output stage of static relays.

Thyristor can be used in several applications such as controlled rectifiers, motor control circuits, temperature control devices a.c./d.c. switch circuits, inverters etc.

In typical thyristors, the range of rated forward current covers a few amperes to several hundred amperes. The thyristor can be triggered by a momentary pulse (4 μ sec) of a few milliamperes gate current. When used in a.c. circuits, the gate current pulse can be timed so as to fire the SCR at the desired angle with each positive half cycle, thereby producing phase control.

38.20.4. Power Switching Techniques with "Thyristors"

Conventional electromagnetic relays and contactors have numerous disadvantages, the moving parts wear out quickly when the rate of switching is high. There is also a danger of arcing across the contacts which demands flame proof enclosure if the contactor is to be installed in explosive atmosphere. Their efficiency can be adversely affected by dust and other air-born contaminants. 'Thyristors' have made possible solid state switching devices. These devices perform the operations performed by electro-mechanical units but with few of their disadvantages.

A.C. and D.C. Switching. A thyristor can be regarded as a conventional diode (rectifier) equipped with a third terminal through which a small pulse of current in injected to trigger it. Unlike the conventional rectifier the thyristor blocks both negative and positive voltages until the trigger signal is applied. Once triggered, the thyristor will pass current in one direction until the end of half a cycle when the current drops to zero. If a second pulse is applied at the next half cycle, the action is repeated. In other words, if the potential across the thyristor is suitable, the thyristor triggers when a pulse is applied to the gate and it continuous to conduct till the potential is suitable. Thyristors can be used for a.c. and d.c. switching application with high reliability. Fig. 38.10 gives diagram of a single phase thyristor switch.

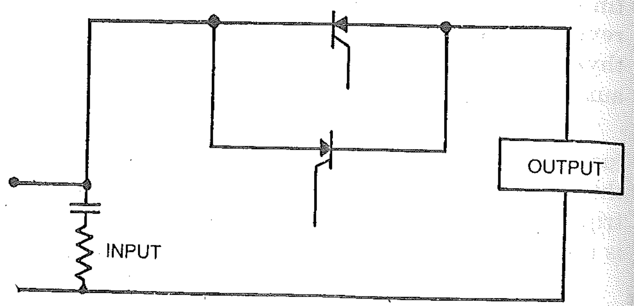


Fig. 38.10. Single phase thyristor switch.

The thyristor conducts for half the cycle when forward biased, provided positive pulse is applied to its gate. At natural current zero of the wave the thyristor automatically turns off. The period of conduction in half cycle can be controlled by controlling the phase of the pulse applied to gate. Two thyristors are necessary to get conduction for full-wave. In d.c. circuit, only a single thyristor of enough rating will be adequate instead of two thyristors shown for a.c. circuit in Fig. 38.10.

38.20.5. Triac

The output element of a static relay can be a *Triac.* Triac is a further development of SCR. Thyristor (SCR) conducts only in one direction (DC) when a positive pulse is applied to its gate; and conducts until the DC supply is interrupted. Triac is bi-directional device and passes current in either direction (A.C.) when triggered by either positive or negative gate signal. Once turned on, the triac conducts till the load current falls to zero. In D.C. circuit load current should be switched off by an auxiliary switch. In A.C. circuit load current reaches zero twice in a cycle.

With signal continuously present on the gate, the triac automatically turns on and off at the beginning and end of each half cycle. Thus the period of conduction is almost a complete cycle.

Since SCR and Triac cuts-off at current zero, there is no problem of switching over-voltages and radio-interference.

38.20.6. Thermistors

Thermistors are used for temperature measurement, temperature compensation circuits. The types include negative-temperature coefficient thermistor and positive temperature coefficient thermistor. The resistance of an n.t.c. thermistor decreases with the increase in temperature.

38.20.7. Resistors

Variable resistors are frequently used in static delays for continuously setting the operating values, time delays etc. Potentiometers are weakers links in relay circuits as regards reliability. Hence care should be taken in choosing the type of potentiometer for particular applications. Wire-wound type is most common. The reliability of this type is high upto a few kilo-ohms value. Carbon-potentiometers which are widely used in other electronic circuits are not suitable for static relays as regards precision and stability.

A new type of potentiometer called cemeto potentiometer is being widely used in static relays. It consists of a semiconducting material.

Carbon resistors are rarely used in static relays. Instead, metal-oxide resistors, metal film resistors and wire-wound resistors are used.

38.20.8. Capacitors

Capacitors are used in time circuits, integrating and differentiating circuits, filter circuits, smoothing circuits, protective-circuits of static relays. The selection depends on desired quality.

In time circuits, high stability and low leakage currents are desired. Plastic dielectric capacitors are, therefore, preferred.

Polycarbonate capacitors are generally used where high stability (better than 1%) is needed. Electrolytic capacitors are rarely used in static relays except in uncritical circuits such as smoothing circuits of feeding devices. Tantal electrolytic capacitors are better as regards stability than common electrolytic capacitors.

Capacitor Units

Separate plug-in modules of capacitor units are used in static protection systems. The standard units can be ordered and kept as spares. Capacitor units are available for

— Auxiliary relay pick-up and drop-out circuits
— For impulse lengthening or shortening
— For feeding trip coils upto 300 W, during interruption of auxiliary power. These units *capacitors* of following type :

(1) Aluminium-Electrolytic Capacitors (wet type)
— 16 V.220 μF to 63 V, 47 μF.
(2) Tantalum-Electrolytic capacitors :
— 6 V, 330 μF to 350 V, 47 μF.

38.21. PRINTED CIRCUIT BOARDS WITH DISCRETE COMPONENTS

The task of connecting the discrete (*i.e.* separate, individually identifiable), components was simplified by using Pre-printed Circuit Boards. Complete circuit is printed and etched on insulating board, and conducting material is filled into eached portion to provide electrical connection between the discrete components (resistors, capacitors, discrete components are inserted in the cavities provided in the board and terminals are soldered. The PCB's can be plugged into a frame in a modular form to get a compact and simple standard assembly. The first generation of static relays was with discrete components. The PBC circuits were much compact than the value circuits. The manufacturing process was also more economical and faster. However the reliability was not entirely satisfactory one to large number of discrete components.

The second generation of static relays was with integrated circuits (IC's). The static relays with IC's are most compact and have higher reliability.

38.22. STATIC RELAYS WITH INTEGRATED CIRCUITS

The hybrid IC's have resistance, capacitance, and *R-C* circuits formed by depositing conducting, semi-conducting and insulating materials on a passive or a neutral base such as glass or ceramic, by process of diffusion, printing/doping. These are not truly monolithic IC's, but a step towards IC's.

Truly monolithic IC has a basic electronic circuit (with its passive elements such as resistors capacitors and active elements such as diodes and transistors) in a single piece of silicon wafer (chip). The entire circuit is formed in a single manufacturing process.

A single silicon wafer of about 25mm diameter can accommodate about ten to hundred IC's made simultaneously, the number depending upon the complexity and size of individual circuits.

The individual IC's are then separated. To give an idea, a complete IC comprising about 12 transistors and associated resistors can be accommodated on a 1.3 mm^2. The IC package containing this circuit and terminals will be about 1.5 mm^2.

Such a circuit is known as Integrated Circuit (IC). Integrated Circuits for common functions are manufactured on large scale as per international standards (IEC 147, 141). Standard IC's are commercially available (Ref. Table 38.3). Integrated Circuits can be broadly divided in two categories.

— Analogue — Digital

Analogue IC's operate on continuous signals and linear range. They are used mainly in operational amplifiers, oscillators, regulators etc. (Ref. Table 38.3). They find application in carrier current protection, and various static relay functional circuits. Digital IC's are principally used as switching units which perform on/off function. These IC's do not require precise components like Analogue IC's. Hence Digital IC's are easier and cheaper to manufacture and are preferred in wide range of applications such as binary logic circuits, switching gates, etc. (Ref. Table 38.3).

Table 38.3. Integrated Circuits

Digital	*Analogue (Linear)*
Inverters	Operational amplifiers
Flip-flops	Peramplifiers
Monostable circuits	A.F. amplifiers
Pulse generators	Z.P. amplifiers
Emitter-coupled circuits	Power amplifiers
Schmitt triggers etc.	Voltage regulators
NAND, NOR, AND, OR Gates	Wideband amplifiers
Transistor-transistor circuits	Level detectors etc.

The digital systems are based on pulse and pulse chain inputs. They are used in logic circuits. Logic circuits are being increasingly used in protective relaying.

Monolithic techniques are used to make ICs (Integrated Circuits). A monolithic circuits is contained within a single crystal. The advantages of integrated circuits compared with discrete circuits* (*circuits where various separate components are connected to form the circuit) include :

(*a*) Higher total reliability as number of soldered points is reduced.

(*b*) Smaller dimensions. (*c*) Generally, lower price.

(*d*) High stability due to uniform temperature in the monolithic circuit.

(*e*) Design is simplified.

38.22.1. Reed Relays

(*i*) **Application.** Reed relays are not static devices. They are used in industrial control Circuits and Switching Circuits. Reed relays are sometimes used in between conventional input device and solid state logic circuits. Reed relays are used in low voltage, low current circuits.

Conventional electromagnetic relays are used in majority of application. However, reed relays are used in logic circuits and where the contacts need the following :

— Sealed construction to overcome problems of dust, humidity, corrosive fumes.

— Faster switching, repeat accuracy.

— Large number of switching cycles.

(*ii*) **Construction.** (Ref. Fig. 38.11) The reed relays consists of a set of pairs contacts on two long flat strips (Reeds) of ferromagnetic material. The other end of reeds are fused into glass tube which is hermetically sealed and filled with inert gas like nitrogen. Contact tips are plated with silver or gold for lowering contact resistance.

The tube is surrounded by a coil. When current flows through the coil, the magnetic field causes magnetisation of the reeds. The contact ends get opposite polarity. Thereby the contact get closed. On removal of the magnetic field the reeds reach the original open state.

In Reed Relay with normally closed contacts, a permanent biasing magnet is placed near the tube. The reads remain closed due to magnetic field of the magnet. When the coil is energised, it gives a magnetic field opposite to that of the permanent-biasing magnet. Thereby the total field is zero and reeds open. When the current in field coil is stopped, the reeds come in closed position due to the field of the permanent magnet.

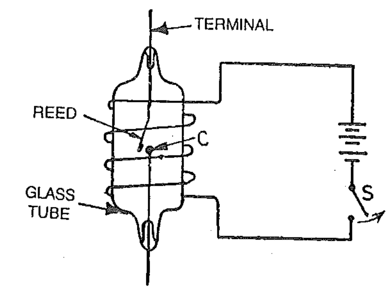
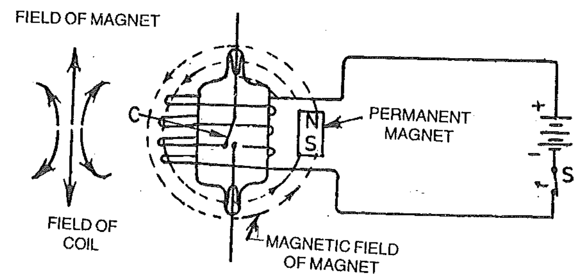


Fig. 38.11 (*a*) Reed relays operated by magnetic coil.
Coil energised — relay closes Coil de-energised — relay opens.



Logic
When
S closed = C open
S opened = C closed

Fig. 38.11 (*b*) Reed relay with permanent magnet and magnetic coil.

(*iii*) **Typical Characteristic of a Reed Relay**

Continuous Current rating (main contacts)	:	0.1 A to a few amperes
Operating time	:	1 ms.
Switching capacity (main contracts)	:	Upto 50 W (recently)
Number of operations	:	10^6
Number of contact-pairs	:	Upto 6

38.23. STATIC DIRECTIONAL UNITS

(*i*) **Hall Generator.** Hall generator consists of a semi-conductor flat crystals usually N-type Germanium, placed in magnetic field created by voltage coils (Fig. 38.12). Current is passed through the crystal, from one edge to the other. A d.c.e.m.f. '*E*' appears the mid-points of the other edges of the crystal (Ref. Fig. 38.12).

The d.c.e.m.f.'*E*' depends upon the phase angle between the flux produced by voltage coil and the current. This property is used to obtain the measurement of phase angle between V and I for directional relays (Ref. Fig. 38.12).

(*ii*) **Magneto-resistors.** These devices have been recently developed. Their resistance depends upon the surrounding magnetic field. This property is utilized in them in using directional units.

— High repetition rate due to rapid response of the elements.

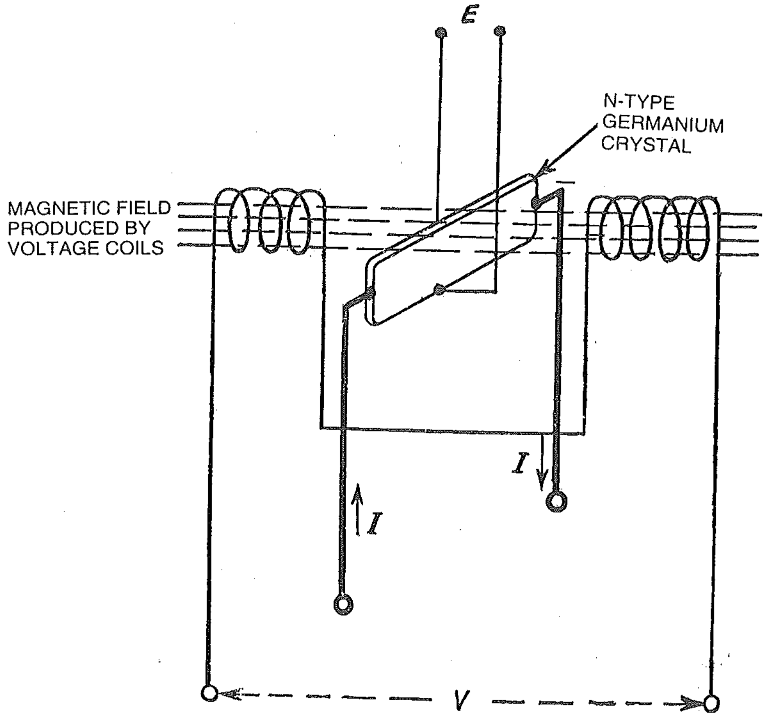
— Unaffected by shock and vibration.

— Require no maintenance of adjustment, space saving.

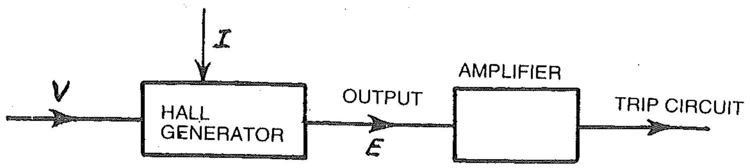
— Can be used in dusty, humid or corrosive atmosphere.

— Enables sequential control circuits to be arranged which memorize their information, even in the case where the power supply is cut-off.

— Complete eliminating of race condition due to non-simultaneity in the operation of closing, opening and inversion of the different contacts of a relay.



(a) Hall generator.



(b) Directional relays unit employing Hall generator.
Fig. 38.12. Hall generator for Directional Protection.

Section II. DIGITAL CIRCUITS AND THEIR APPLICATIONS IN PROTECTIVE RELAYING

38.24. LOGIC CIRCUITS*

Complex protective relays can be achieved by means of logic approach. A switching circuit may be though on in terms of the schematic Fig. 38.13.

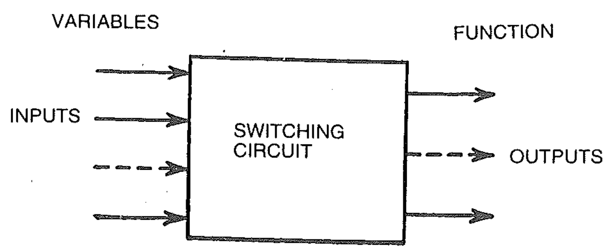


Fig. 38.13. Schematic diagram of a logic circuit.

* Ref. Sec. 44.14, Table 44.2 for symbols.

Each input and output line must be in one of the two possible states at any given time. For instance a line may be 'on or off', *i.e.* 'conducting, or 'non-conducting'. The output of a logic circuit is a function of its input. We will not bother about why the circuits behave that way, but only see how they operate.

Switching circuits are made up of interconnection of basic 'logic blocks'. Five common functions are performed by logic blocks used in static relays and computers, these are

AND OR NOT NAND MEMORY. Logic units can be used in all fields of "on and off" control. They are particularly suitable for the following applications : (Ref. Sec. 44.14)

— Installations requiring fairly complicated sequences of operation; the use of static logic elements is particularly interesting in complex problems or in those which involve a large number of variables, *e.g.*, Auto-reclosing schemes.

The term *logic variable* is used for a quantity which expressing these states, can only two distinct values, conventionally designated 0 or 1. This quantity can occur in the form of a voltage of the terminals of a circuit, a current in the coil of a relay or electrovalve, illumination of a photo-electric cell, opening or closing of a relay contact or a limit switch stop etc.

These functions will be explained here with the diagram-symbol and the truth-table of each.

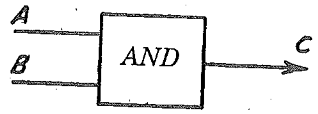
38.25. AND FUNCTION (Ref. Table 44.2 *a*)

The function is equal to 1 when all the variables are equal to 1.

The function is 0 when one or more varial is 0. Here '1' and '0' denote the two states such as conducting, non-conducting or positive and negative.

Logic Truth Table

A	B	$C = A$ *and* B
0	0	0
0	1	0
1	0	0
1	1	1



$C = A$ and D
Fig. 38.14.

AND function is represented by the symbol $\wedge$ *e.g.*, $x \wedge y$ means x and y. [Symbols $\wedge$, $+ \cap$ are used for *AND functions*]. Consider two statements A and B.

The entire statement can now be written as 'A and B' or '$A \wedge B$' where

If A is true 1.

If A is false 0.

If B is true 1.

If B is false 0.

Truth Table AND function

A	B	$A \wedge B$
1	1	1
1	0	0
0	0	0
0	1	0

AND Circuit. The output C is positive + if all the inputs are positive. Output is negative if one or more in inputs are negative.

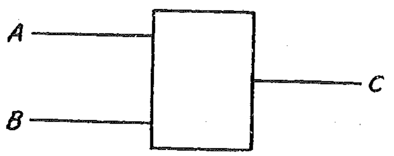


Fig. 38.15

Voltage Truth Table

A	B	C = A ∧ B
–	–	–
–	+	–
+	–	–
+	+	+

Fig. 38.16 illustrates a logic AND gate achieved by Diodes. It is called Diode Logic. This gate can be achieved either by a discrete component circuit or by integrated circuit (IC).

AND Circuit

Truth Table (Ref. Fig. 33.16)

A	B	C
–	–	–
–	+	–
+	–	–
+	+	+

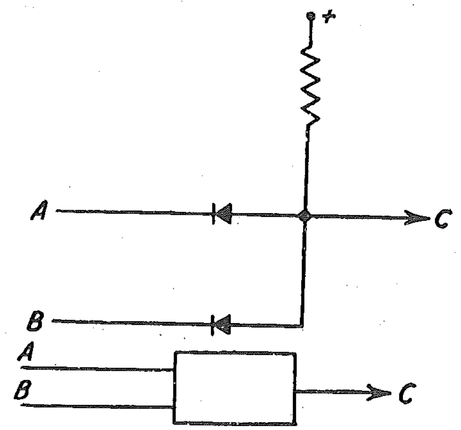


Fig. 38.16. AND circuit using diodes.

The input terminals have one of the two states called.

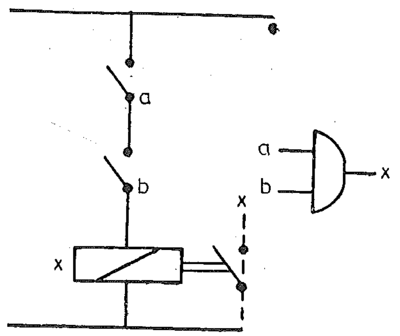
high	low
+	–
1	0

The output also has two states.

Consider the logic of the Fig. 38.16. When both V_A AND V_b are high (+, 1) the two diodes are reverse biased. Hence the current does not flow through resistor and the output C is at high (+ or 1).

Hence when V_A AND V_B are +, the output V_c is +. This is AND function drops to low (–, 0)

Fig. 38.17 illustrates AND gate employing contact a, b and contactor X. When a AND b are closed, contactor X closes contacts x.



a	b	x
0	0	0
1	0	0
0	1	0
1	1	1

$Fx = a \cdot b$

Fig. 38.17. AND gate with conventional contacts a, b and contact X.

38.26. OR FUNCTION (Ref.Table 44.2 b)

Consider the two statements A and B.

A = Mohan is an Engineer   True = 1, False = 0
B = Mohan is a Doctor   True = 1, False = 0
C = Mohan is an Engineer or a Doctor.
A or B is written in $A \vee B, A \cup B$

Logic Truth Table

A	B	C = A or B
0	0	0
0	1	1
1	0	1
1	1	1

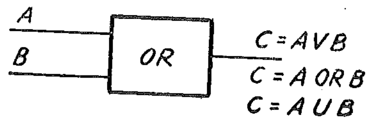
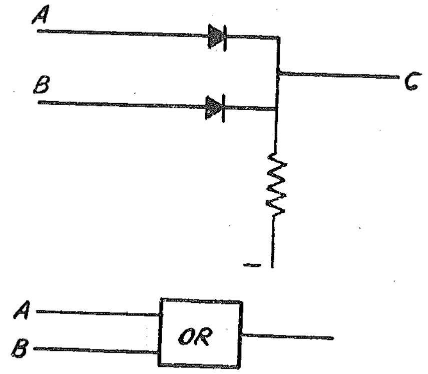


Fig. 38.18.

The function equals 1 if one or more variables equal 1. Conversely the function is zero if all the variables are zero.

Or Circuit with Diode

In Fig. 38.19 the output C is positive if inputs A OR B is positive. Otherwise C is negative.

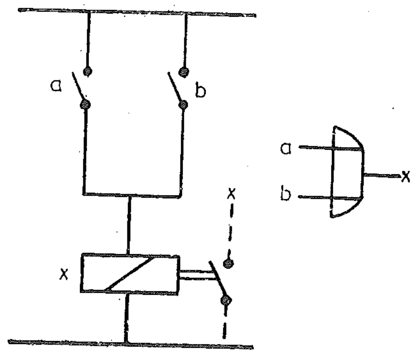


Truth Table

A	B	C = A OR B
–	–	–
–	+	+
+	–	+
+	+	+

Fig. 38.19.

The OR operation is performed by contacts in parallel in conventional relay systems. Relay X in Fig. 38.20 picks up and produces and output signal at its normally open contact X when of the contacts a OR b is closed.



a	b	x
0	0	0
1	0	1
0	1	1
1	1	1

$Fx = a + b$

Fig. 38.20 OR circuit with conventional contacts a, b and contactor X.

38.27. NOT FUNCTION (Ref. Table 44.2 *c*)

This function is negative *e.g., Mohan is not a child.* NOT function is signifies negation

A	$C = \bar{A}$
0	1
1	0

NOT function

Fig. 38.21

Statement A = Mohan is a child.

$\bar{A}$ means not A.

The function is equal to 1 when single variable is zero. The function equals zero when single variable is to 1. Hence

NOT function signifies that the incoming signal and output signal are inversed. In Fig. 33.22, when contact A of conventional relay is closed, contact C of contactor C' is opened. When A is open, C is closed. In other words $C = A$, *i.e.* C = NOT A.

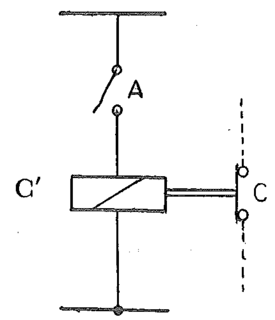


Fig. 38.22. NOT Function with convention relay contact *A* and contactor contact *C*.

38.28. COMBINED FUNCTIONS (Table 44.2 *j, k*) .

About 75% logic operations can be achieved by logic gates AND, NOT, OR. These are used on combinations :

NAND = NOT AND NOR = NOR OR

'NAND' Function. NOT AND is shrinked to NAND. Its Boolean Symbol is | . For example $A \mid B$ or $\overline{AB}$ or $\bar{A} + B$.

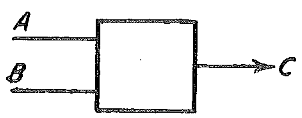


Fig. 38.23

Truth Table

A	B	C
–	–	+
–	+	+
+	–	+
+	+	–

A	B	$C = \overline{AB} = \bar{A} + \bar{B}$
0	0	1
0	1	1
1	0	1
1	1	0

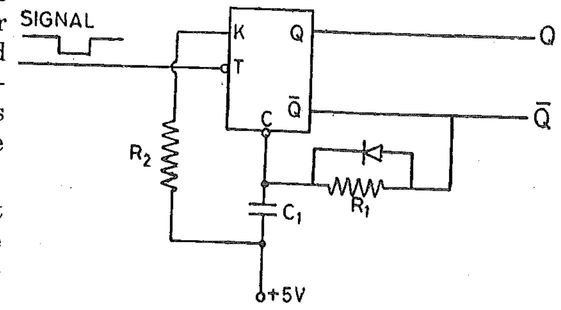
'NOR' Function. NOR is a combination of NOT OR. Boolean symbol is ↓ *e.g.* $A \downarrow B$.

A	B	$B = \downarrow B$
0	0	1
1	0	0
0	1	0
1	1	1

A	B	$B = A \downarrow B$
–	–	+
+	+	–
–	+	–
+	+	–

38.29. MEMORY FUNCTION (STORAGE FUNCTION)

The memory unit retains the binary signal for a definite or indefinite period of time. In conventional relays, a self-holding contactor retains its contacts in closed position retains the memory for a short duration of time and a magnetically latched contractor for an indefinite time. These are monostable or single short functions. Storage functions have two states : 'set and cleared'. These states are either of definite time or indefinite time.



(*a*) Monostable Circuit.

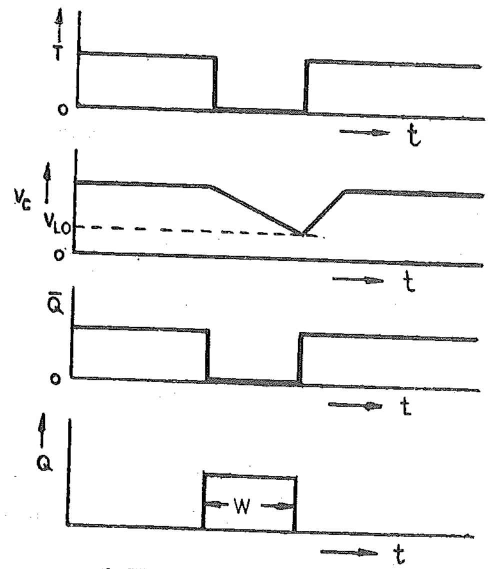
(*i*) **Monostables.** These have a single input pulse. The 'monostable multivibrator' or 'single shot' (because it gives a single pulse). In conventional relays, the definite time storage with a single pulse is achieved by *RC* element. A single can be delayed by a *RC* network or a time-delay relay. If a pulse is applied to the input of such a time an output pulse having a limited period *T* is produced. The period of *T* is determined by the *RC* element. The output signal can be delayed by combining the timer with other basic functions. Fig. 38.24 (*a*) illustrates a typical circuit which generates a pulse in response to a trigger pulse. The width *W* of the output pulse is adjustable. This circuit can be called as monostable or monostable multi-vibrator.

In Fig. 38.24, the output Q of the flip-flop is connected to clear C through resistor R_1.

Because of this connection this circuit has only one stable state $q = 1$ and $Q = 0$.

If Q does becomes zero, the voltage V_c decays towards zero until V_{10} stage is reached [Fig. 38.24 (*b*)]. At this instant, the flip-flop clears and $\bar{Q}$ goes back to 1 and Q goes to zero.

Thus the state with $Q = 1$ and $\bar{Q} = 0$ is unstable and persists for a pulse with *W* which depends upon R_1C_2 time constant.



(*b*) Wave forms of Monostable.
Fig. 38.24. Monostable.

In static relay circuits, monostables are used for a variety of timing application such as production of pulses of specified width, production of delayed waveforms etc. For example, the trigger *T* given to a triggering circuit (Ref. Fig. 38.24) could be used to produce a pulse of width *W* required in a particular application.

(*ii*) **Flip-flop Bi-Stables.** Two NAND gates can be connected back-to-back in such a way that the output of one element is connected to the other element and *vice verse.*

In set-reset flip-flop (*S-R* flip flop). (Ref. Fig. 38.25)

If both S and R are held at 1, the Q and $\bar{Q}$ continue their respective earlier state. If S is kept 1 and R is set to 0, Q will be forced to zero and Q will be forced to 1. If R is returned to 1, without changing S from 1, the output state remains indefinitely $Q = 1$ and $\bar{Q} = 0$.

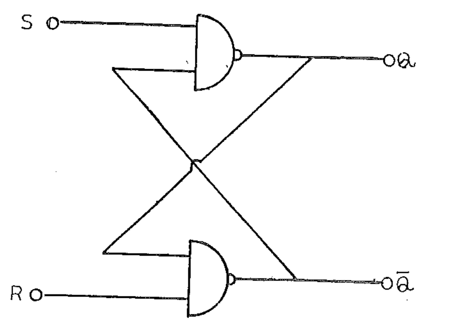


Fig. 38.25. Set reset flip-flop using NAND gates.

Similarly if R is kept 1 while S is set zero output is forced to 0 while $\overline{Q}$ becomes 1. If S is returned to 1 and $Q = 0$. $\overline{Q} = 1$ persists. Thus by applying the correct pattern 1 - 0 to S-R inputs the desired state can be achieved at Q. *The circuit retains that state until an appropriate input is changed.*

In other words, the flip-flop circuit retains the binary signal and has a memory.

38.30. FAMILIES OF LOGIC CIRCUITS

The logic functions can be achieved by applying the following elements. Accordingly, the family or logic circuit is named.

— *Diode-Transistor Logic DTL*

incorporates diodes and transistors to achieve the logic function

— *Transistor-Transistor Logic (TTL)*

incorporate Transistors.

— *MOS Transistor Logic :*

Employ metal oxide-semiconductor (MOS) Logic employes MOS transistor and diodes instead of bipolar (junction) semiconductors.

(*i*) **DLT Logic (Diode Transistor).** Fig. 38.26 illustrates a basic NAND gate circuit. Transistor NPN conducts when base has positive polarity with respect to emitter when both inputs V_a and V_b are (+) high, the current flows through the circuit $+V D_1, D_2$ into base of transistor causing its saturation. The transistor conducts and voltage of terminal V_x is then close to ground potential. Thus the gate acts according to following logical function :

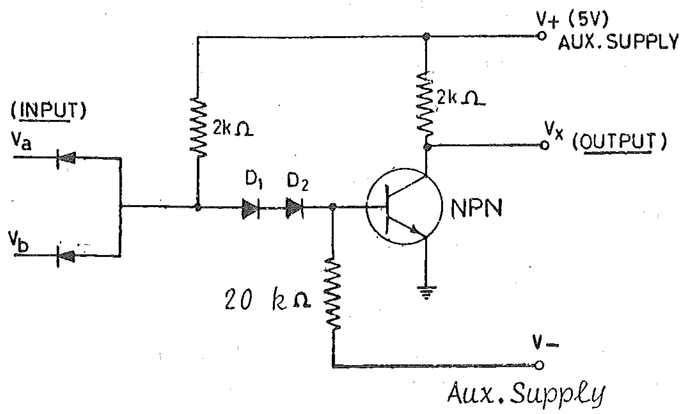


Fig. 38.26. NAND gate with DTL.

V_a	V_b	V_x
0	0	1
0	1	1
1	0	1
1	1	0

Where $V_x = 1$ represents high potential or V_x and $V_x = 0$ represents ground potential of the V_x. This is a NAND logic function. Diode D_1 and D_2 do not conduct till the voltage V_1 does not exceed 1.4 (0.7 + 0.7). This prevents wrong operation of the gate due to spurious signals. The propagation delay time of a typical DTL gate is 30 nenoseconds. It is moderately slow, but quite adequate for protective relaying applications. DTL logic gates family includes AND, OR, NAND, NOR gates. These can be in form of Discrete Component Circuits or Integrated Circuits. Thereby DTL family provides a vast scope to the designer of Logic circuit to design any logic sequence. Unused input are either connected to ground or to 5 V (+).

(*ii*) **TTL Logic (Transistor-Transistor Logic).** Transistor-Transistor Logic Circuit family is exclusively of Integrated Circuits (IC's) and is not possible with discrete components. A basic TTL

gate circuit is shown in Fig. 38.27. The circuit contains a Multi-emitter input transistor (which is possible only in Integrated Circuit and not in discrete component), in which the collector currents is the sum of two emitter currents. The multi-emitter input transistor has behaviour similar to single emitter transistor.

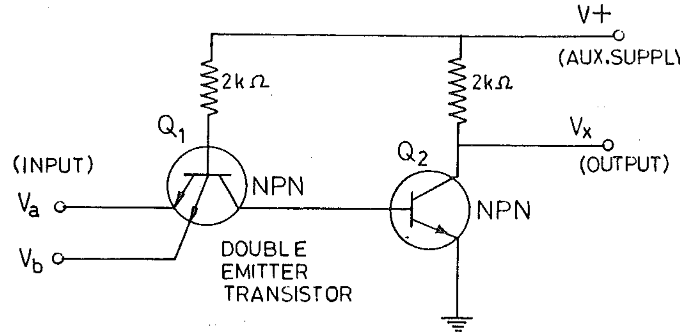


Fig. 38.27. NAND gate with TTL (Transistor-Transistor Logic).

When either of V_a and V_b is low (corresponding to 0) the transistor Q_1 will have a positive current i_1. This will drive the transistor Q_2 into cut-off state and input V_x will rise to + 5 V (corresponding to state).

When both V_a and V_b are raised to 5 volts (*i.e.* 1 state) then the base collector part of Q_1 gets forward biased and base-emitter part of Q_2 gets reserve biased. This results in reversed operation of input transistor Q_1. The current i_1 is reversed and becomes negative. Output transistor Q_2 is driven into saturation. (It conducts from collector to emitter much larger current and collector to emitter impedance drops down to a low value). Thereby output V_x drops to earth potential (state 0).

The truth table of this gate corresponds to NAND operation.

Truth Table of Gate in Fig 38.27:

V_a	V_b	V_x
1	1	0
0	1	1
1	0	1
0	0	1

When V_a and V_b is high, V_x is low

V_a and V_b is not V_x

This is NAND function.

(*iii*) **Metal Oxide Semiconductor Logic (MOS).** In this family of logic circuits, enhancement mode MOS transistors are used instead of junction transistors. (Ref. Section 38.9 *b*)

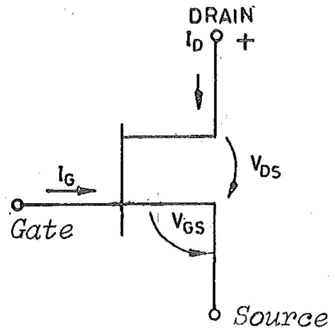
MOS transistors can be used as ON-OFF switches. Low current part of MOS transistor characteristics can be used as resistance. Thus it is possible to fabricate all resistor, switches and transistors with MOS family.

MOS logic is slower than other logic families (TTL/DTL).

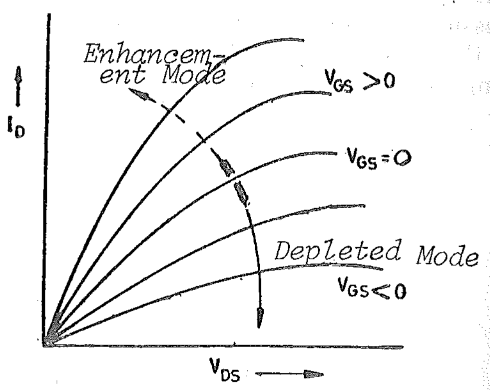
However MOS logic has several advantages such as :

— it requires less power.

— it needs only a fraction of area required by other logic gates. This leads to large scale integration IC's. (LSI-IC's). In MOS-LSI integrated circuits a single chip may contain thousands of transistors.



(*a*) Symbol of MOS.



(*b*) Characteristic of MOS

Fig. 38.28. Metal. Oxide Semiconductor (MOS).

Pocket calculators with MOS-LSI circuit can perform computation, logic and control functions.

COS/MOS logic gates (complementary symmetry MOS Logic) have both *p*-type and *n*-type channels. COM/MOS logic gates are available in NAND, NOR and many complex functions. Unused inputs are connected to positive or negative supply illustrate symbol and characteristic or a COM/MOS inverter.

MOS logic is used in recent digital circuits for static relays.

38.31. APPLICATIONS OF LOGIC CIRCUITS IN PROTECTIVE RELAYING

Logic functions AND, NOT, OR MEMORY INVERT, NAND, NOR etc., can be conveniently used for the following :

- in measuring circuit of relay, in comparators.
- in auxiliary systems for interlocking and control functions (To replace auxiliary and all or nothing relays)
- for starting and control of power consuming devices.
- for control of power plant and generating systems.
- in conjunction with digital computers for remote on-line monitoring of back-up protections of system components.

Some of these applications have been covered in section IV.

Consider auto-reclosure of a circuit-breaker. The sequence is as follows :

(Ref. Sec. 44.14, Fig. 44.11).

If fault has continued, open the circuit breaker. If fault has not continued, let it remain closed. So, the circuit breaker has two alternatives. (To REMAIN CLOSED) OR (TO OPEN)

The static auto-reclosure system suitable for auto-reclosure scheme can incorporate an OR gate, alongwith other components.

In static comparators, the two inputs to be compared can be fed into an NAND gate. The output of the AND gate can be given to other circuit components. (Ref. Ch. 39)

In complex protection schemes, various logic gates are used.

Section III. OPERATIONAL AMPLIFIERS AND ANALOGUE CIRCUITS

38.32. DEFINITION AND APPLICATION

The term 'operational amplifier' is used widely to denote a circuit containing a high gain d.c. amplifier with a feedback from output to input. The operational amplifier circuit comprises tran-

sistors, registors and capacitors connected in suitably form and satisfies the following basic conditions :

- very large Thevenin's Equivalent Input impedance (Ref. Sec. 19.13) and resistance.
- very small Thevenin's Equivalent Output impedance and resistance.
- Operates linearly over its working range as high gain voltage amplifier.

Operational amplifier is an Analogue circuit which operates on continuous input and in linear range.

A basic operational amplifier is represented by a triangle having two input terminal and one output terminal. (D.C. supply is not indicated in the symbol).

The basic operational amplifier (the triangle) circuit is available in readily built modules (either discrete or IC's). Such modules can be connected with appropriate feedback circuit to achieve mathematical function such as :

- addition, subtraction,
- integration,
- differentiation,
- combination of the above.

Operational Amplifiers are widely used in analogue circuits to instrumentation, control on protective relaying. While studying application of Operational Amplifiers it is not essential to be familiar with the internal circuit of the same (triangle). But the function of the operational amplifier (triangle) with respect to the external terminals must be clearly understood for understanding the application.

38.33. SYMBOL OF OPERATIONAL AMPLIFIER

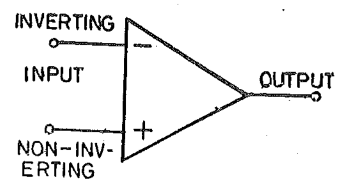


Fig. 38.29. Symbol of an Operational amplifier.

Fig. 38.29 gives the symbol of an operational amplifiers. Most operational amplifiers have several terminals in addition to those shown in the basic symbol. The addition terminals are for connection to external circuit to achieve near-ideal behaviour. Operational amplifier has two input terminals. The negative terminal is called 'Inverting Input'. The positive terminal is called 'Output Terminal'. Supply terminals (usually not shown in block diagrams) get d.c. supply from batteries or regulated power supply. Usually only one output terminal is indicated, the other terminal of load being earth (ground).

38.34. CHARACTERISTICS OF IDEAL OPERATIONAL AMPLIFIER

An ideal operational amplifier has infinite input resistance, a zero output resistance and voltage characteristic illustrated in Fig. 38.33. Infinite input resistance results in zero input current. The zero output resistance means, the voltage drop in output stage is zero. The circuit model for ideal operational amplifier can be represented by Fig. 38.30 (*a*).

In linear range,

$$V_o = A\,(V_+ - V_-)$$

where A = voltage gain usually 10,000

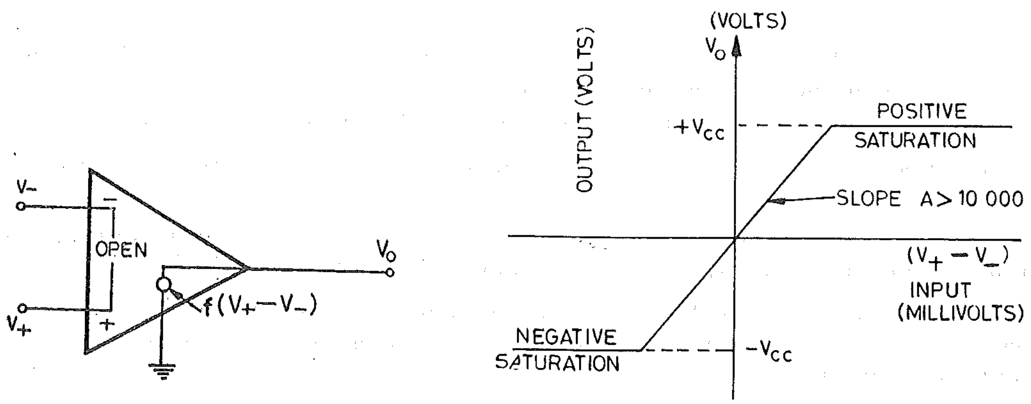
V_+ = inverting input

V_- = non-inverting input.

From Fig. 38.30 (*b*) it can be seen that in ideal operational amplifier a very small input voltage brings a saturation. This draw-back is overcome by negative feedback.

*Ref. Fig. 38.52 (*a*), when $V_A + V_B \neq 0$

Negative sequence current output of the filter, $I_2 \neq 0$.



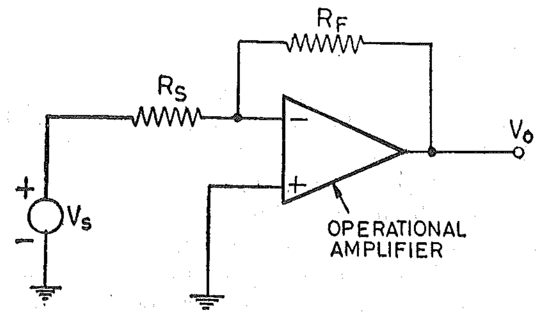
(*a*) Circuit Representing ideal Operational Amplifier.

(*b*) Typical Transfer Characteristic of an Operational Amplifier. (Output saturates at supply voltage. Linear range input voltage is very small).

Fig. 38.30

38.35. SOME APPLICATIONS OF OPERATIONAL AMPLIFIERS

(*i*) **Inverting Amplifier.** (Fig. 38.31)



$V_0 = -\frac{R_F}{R_s} V_s$

$V_0 = V_s$ for $\frac{R_F}{R_s} = 1$

Fig. 38.31. Use of Operational Amplifier as an inverter.

The output is fed back to negative input through a resistance R_F.

$$V_0 = \frac{R_F}{R_s} V_s$$

The effect of negative feedback is

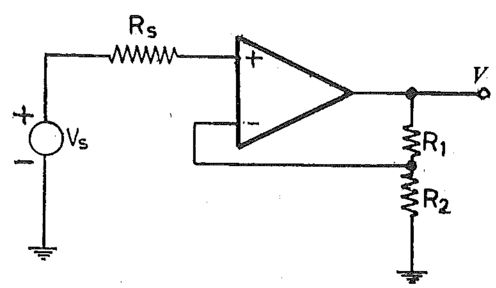
— to reduce gain and make it independent of open circuit gain *A*.

— to permit relatively large input voltage V_s without saturation.

— to produce an inverting closed loop gain R_F/R_S.

(*ii*) **Non-Inverting Amplifier.** (Fig. 38.32)

Feedback is applied to negative terminal through R_1. Input is supplied to positive terminal through R_s.



$$V_0 = \frac{R_1 + R_2}{R_2} V_s$$

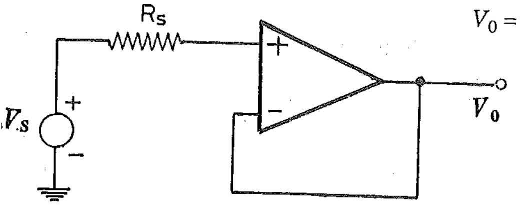
Fig. 38.32. Non-inverting Amplifier.

If R_2 is infinite, V_0 tends to zero. If R_2 is zero, V_0 tends to infinity.

(*iii*) **Follower.** (Fig. 38.33)

Output terminal is connected to input negative. Input is connected positive through R_s.

The output voltage 'follows' input.



$V_0 = V_s$

Fig. 38.33. Follower.

(*iv*) **Analogue Addition.** (Fig. 38.34)

$V_0 = V_s$

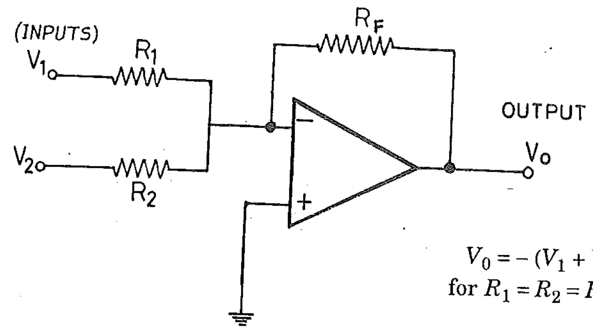
The waveforms V_1 and V_2 are added by means of addition circuit.

If R_F, R_1, R_2 equal

$$V_0 = -(V_1 + V_2)$$

$$V_0 = \left(\frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2\right)$$

If R_F, R_1, R_2 equal, $V_0 = -(V_1 + V_2)$



$V_0 = -(V_1 + V_2)$
for $R_1 = R_2 = R_F$

Fig. 38.34 Analogue Addition.

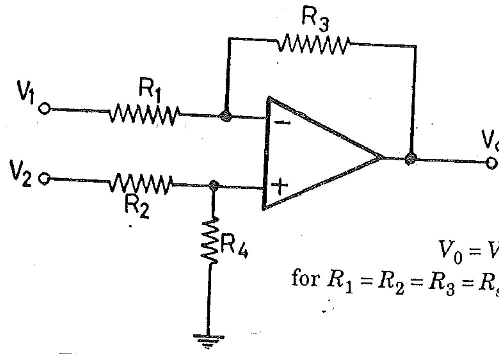
(*v*) **Analogue Subtraction.** (Fig. 38.35)

The waveform V_1 and V_2 can be subtracted by a suitable circuit of operational amplifier.

$$V_0 = \left(\frac{R_1 + R_3}{R_1}\right)\left(\frac{R_4}{R_2 + R_4}\right) V_2 - \left(\frac{R_2}{R_1}\right) V_1$$

If R_1, R_2, R_3, R_4 are equal,

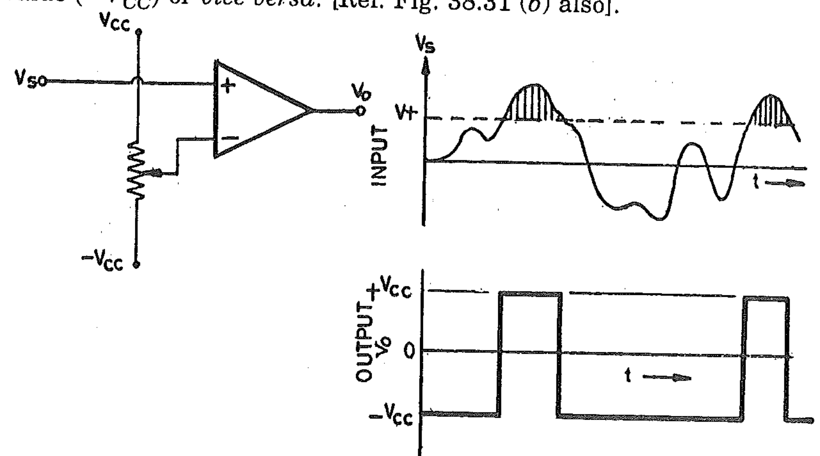
$$V_0 = V_2 - V_1.$$



$V_0 = V_2 - V_1$
for $R_1 = R_2 = R_3 = R_s = R_4$

Fig. 38.35. Analogue Substration.

(*vi*) **Analogue Zero Detector.** Operational amplifier can be used as zero detector by a simple circuit illustrated in Fig. 38.36 (*a*) when V_s touches zero, output V_0 swings from positive saturation (+ V_{CC}) value to negative saturation value (– V_{CC}) or *vice versa*. [Ref. Fig. 38.31 (*b*) also].

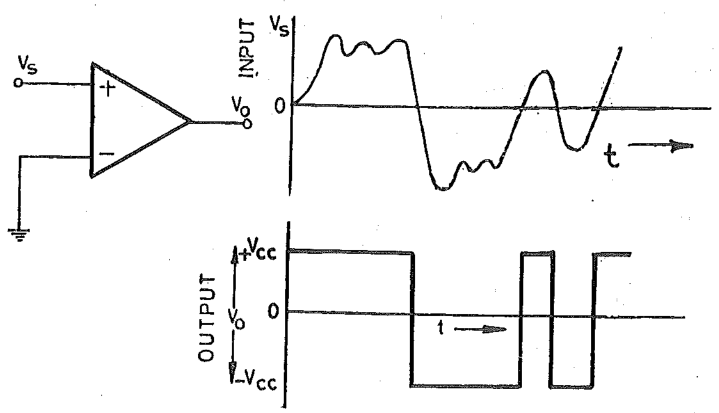


(*a*) Symbol (*b*) Characteristic

Fig. 38.36. Analogue zero detector.

38.35.1. Analogue Level Detector or Comparator (Fig. 38.37)

An analogue comparator can be arranged to compare the instantaneous value with preset threshold value.



(a) Symbol (b) Characteristic

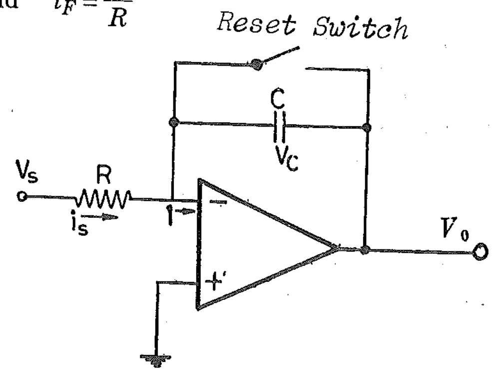
Fig. 38.37. Analogue level detector.

If V_s is more than threshold value V_t, the output of comparator is positive ($+ V_{cc}$). The output V_0 swings from $+ V_{cc}$ when the V_s crosses V_1 and becomes less than V_t. (Ref. Sec. 39.11).

(*vii*) **Analogue Integrated by Operational Amplifier.** An operational amplifier along with a resistor and capacitor can be arranged to integrate input voltage with respect to time (Fig. 38.38).

where i is the current flowing in capacitor. As flows through capacitor only ($i = 0$ due to infinite input impedance),

$$i_s = \frac{V_s}{R} \quad \text{and} \quad i_F = \frac{V_s}{R}$$



$$V_0 = \frac{-1}{RC} \int_0^t V_s \, dt$$

Fig. 38.38. Analogue integrator.

$Q = CV$

The charge on the capacitor C is given by $\int_{-\infty}^{t} i \, dt$

Total charge on capacitor

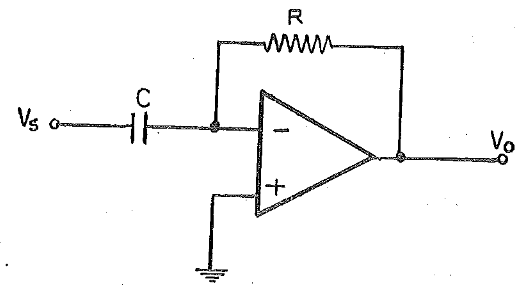
$$Q = \int_{-\infty}^{t} \frac{V_s}{R} dt$$

but $Q = - CV_0$

Hence $$CV_0 = \int_{-\infty}^{t} \frac{V_s}{R} dt$$

$$V_0 = -\frac{1}{RC} \int_{-\infty}^{t} V_s \, dt.$$

This is an integration of waveform. A switch is added to permit discharge of the capacitor resetting the output to zero.



$$V_0 = -\frac{1}{RC} \int_0^t V_s \, dt$$

Fig. 38.39. Analogue differentiator.

(*iii*) **Analogue Differentiation by Operational Amplifier.** Input current it does not flow in input terminal. The input current is given by

$$C \frac{dV_s}{dt}.$$

The circuit is an inverting amplifier (Sec. 38.15.4) with a differential function added in input. Hence

$$V_0 = - RC \frac{dV_s}{dt}$$

This is a differentiation of input voltage.

38.35.2. Analogue/Digital Conversion

(*i*) **Signals processing systems.** The static relay circuits incorporate signal processing systems. A signal processing system is an interconnection of components and devices that can accept an input signal or a group of input signals and act in such a way so as to extract or improve the quality of the information and deliver the output information in the proper form at proper time.

Fig. 38.40 illustrates the basic blocks in Signal Processing System. The continuous signals (derived from secondaries of CT's or PT's, transducers etc.) are called analogue signals as they are similar or comparable to original entity. They are fed to the analogue signal processing block.

The digital signals received from digital computer, from digital protective relay circuit etc. are fed into the Digital Signal Processing block.

The analogue processing block and digital processing block are interconnected through A/D and D/A conversion block. (A/D = Analogue to digital and D/A = Digital to analogue).

Consider a protective relaying system comprising analogue input derived from secondaries of CT's, PT's or tranducers like thermocouple, pressure transducers. "Transducer" is a device which converts physical variables (either electrical or mechanical) to any equivalent voltage or current signal. Some transducers require same form of electrical supply for excitation.

In analogue system the signals (waveforms) are processed continuously. Output of Analogue Processing Block can be in many forms. It can be in analogue form such as measuring instrument, recorders, analogue black and with or coloured display on control boards, *comparators/level detectors of protective relays.*

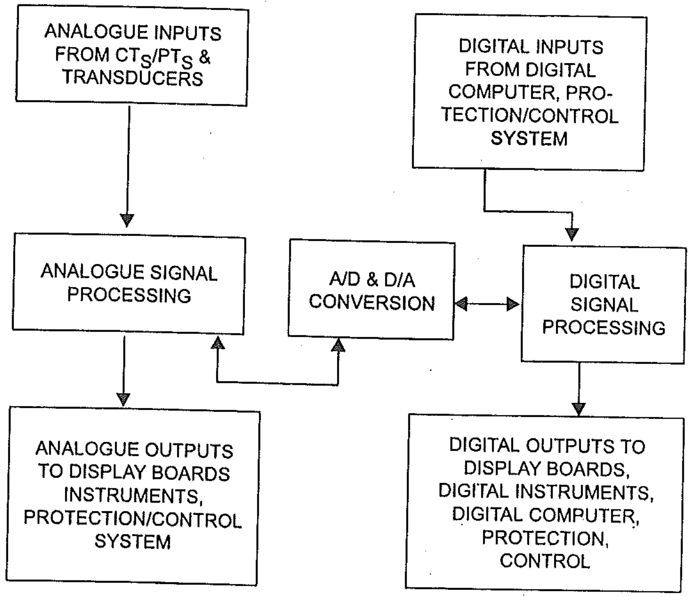


Fig. 38.40. Interaction between analogue and digital systems in power system protection and control.

Alternatively the analogue signals can be converted into representative digital signals and then fed to the digital computer, digital display devices, digital process control devices or *Digital Protective Relaying Circuits.*

In protective relaying systems, the input variables are compared in a 'comparator' the output of comparator is given to 'level detector' the output of level detector is given to 'Amplifiers' and finally, the output of amplifier is given to output (Tripping) stage.

The protective relay system may be purely analogue system as in conventional electromagnetic relays and many simple protection systems. However, in complex protective systems having several input variables and functional requirements, it becomes necessary to use digital systems and digital computers. In such cases the input analogue signals are converted into representative digital signals.

The representative digital signals are supplied to digital measuring instruments, digital display boards, digital control units, digital circuits of protective systems.

(*ii*) **Analogue to Digital Conversion.** There are many methods of analogue to digital conversion. The concept of a simple scheme is illustrated in Fig. 38.41.

The input signals is given to + of operational amplifier. The output of the operational amplifier is connected to a up/down counter.

This type of counter counts up when the control line is high and counts down when control line is low. The up and down counter receives continuous pulses from a clock when the counter undergoes a change of one up or down count, the comparator (Ref. Ch. 39) output reverses in sign and the output of the A/D converter becomes stable.

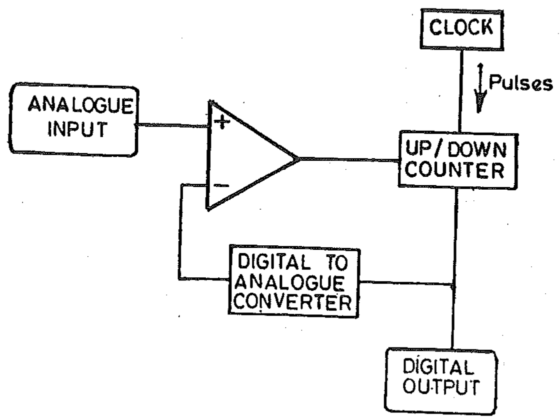


Fig. 38.41. An analogue to digital converter.

38.35.3. Digital to Analogue Conversion

The output of D/A convertor gives analogue signal proportional to the digital input.

38.35.4. Digital Multiplexers

The primary function of combination logic is to produce an output which is combination function of input, variables. If the system has 'n' inputs, there will 2^n combination of inputs and each combination will assign a specific value to the output. This type of operation is performed by digital multiplexer.

Digital multiplexer is a multi-input, single output combination of logic circuit. In digital multiplexer, the logic signal from input is directed towards output as per the *signal routing.*

The signal routing action of the multiplexer is controlled by the external logic signals applied to the selection control inputs which can be considered as the input variables for the device.

In practice the inputs are 2^n numbers where n is limited to 2, 8 to 16. Multiplexers provide general signal routing and its function is controllable externally.

Multiplexers are widely used as general purpose combination logic devices. A 2^n to 1 multiplexer can be used to implement any logic function with n input variables using suitable direct mapping.

The truth table of a 4 input-output Multiplexer is given below :

Channel	*Input Variables*			*Sum at output*
	Selection control		C_1	
	x_1	x_2		
0	0	0	0	1
1	0	1	0	1
2	1	0	0	1
1	1	0	1	0
3	1	1	0	0
	1	1	1	1

A multiplexer's signal routing capability is an important feature in digital protection and control systems. The multiplexer's signal routing is used in microprocessor-based and digital computer based protection and control systems to route the date from data bus structure to relevant functional circuits *via* the communication bus. Multiplexers are commonly used in microprocessors and digital computers to connect and route on common data highway or bus system and to apply *time division multiplexing* different classes of information along these bus systems.

38.35.5. Encoders and Decoders.

Combination of circuits are usually necessary to produce more than one output from the given set of inputs variables.

An *encoder* generates n outputs from 2^n inputs.

A decoder generates 2^n outputs for 'n' inputs.

Decoders are used extensively in programmable static relay circuits and computers to enable addressing a specific device or element in the system.

For example a microprocessor (Central Processing Unit) will communicate with a particular device or element *via* bus structure with the help of address decoder.

38.35.6. Programmable System

A digital system processes signals or data according to 'program'. The various functions include data collection, data transfer, data storage, data processing by *arithmatic* means, given output etc. These functions are performed internally in the digital system. These functions are performed by appropriate configurations of combinational and sequential logic circuits including memory elements. In programmable systems, the configuration of the general purpose logic is flexible. The hardware is controlled by a programme or sequence of instruction codes which defines the sequence of operations of processing functions. The instruction codes are sorted in the memory part of the system. The function of programmable system can be changed by changing the programme.

38.35.7. Microprocessor [Refer Ch. 43-B]

The advances in digital electronics and computing systems have resulted in development of complete Central Pocessing Unit (CPU) of a computer on a single Integrated Circuit (IC) called a chip. Such a CPU is called a microprocessor or processor and is designated as µp. Microprocessor is an advanced programmable logic device. In static protection systems special microprocessor are incorporated to perform specific functions.

38.35.8. Microprocessor Module [Ref. Ch. 43-B]

The heart of a microprocessor-based protective relay is a microprocessor. For example in a Programmable Distance Relay for protection of transmission line, a 16 bit microprocessor operating at 10 MHz is used.

The microprocessor has a separately replaceable programme memory in the form of chips. The subsystems also include read and write memory for working storage and nonvolatile RAM for storing settings and targets when the relay is de-energized. Included on the processor is the Analog to Digital Conversion system and multiplexer. AC input quantities (4 currents and three voltages) are analogue multiplexed to single sample/hold circuit. The sample/hold subsystem output is fed to an *A/D* subsystem which yields 15 bits dynamic range. Each ac input is sampled 8 times per cycle (1/50 sec).

The single Microprocessor based protective relay described above can perform several on-line functions including :

— Overcurrent supervision
— Power swing blocks
— Time delay
— Loss of potential supervision
— Fault type identification
— Distance protection, etc.

The digital programmable relays have several analogue, digital components and microprocessor. Ref. Ch. 43-B for Microprocessor based Protection.

38.35.9. Hybrid of Analogue and Digital Systems

The static relay systems receive analogue signals from CTs, VTs and other tranducers. Also from remote terminals (*e.g.* from other substation) digital signals are received. Hence, the inputs are digital and analogue. The functions within the relay include analogue multiplexing, analogue comparison etc. as well as digital logic, digital processing etc. Hence the protective system are 'hybrid' systems of analogue and digital.

The Analogue/Digital hybrid Systems can perform the functions by four different techniques.

1. Continuous space, continuous time.
2. Discrete space, continuous time.
3. Continuous space, discrete time.
4. Discrete space, discrete time.

Technique 1 is not suitable for analogue, digital and hybrid computation.

Techniques 2 and 3 require digital and analogue hybrid system. The digital subsystem handles discrete variables and analogue subsystem handles the continuous variables.

Technique 4 works purely on discrete space and discrete time. Therefore it requires a digital computer within the protective system. (Sec. 46.15. Fig. 46.7).

Section IV. ELECTRONIC CIRCUITS COMMONLY USED IN STATIC RELAYS

38.36. AUXILIARY VOLTAGE SUPPLY FOR STATIC RELAYS

The static relays require auxiliary d.c. supply; which is generally obtained from station battery system. The station battery system is also used for other purposes such as tripping, control etc.

Most static relays require various auxiliary d.c. voltage between 24 V and 240 d.c. The voltage stabilizers are used in the circuit of relays. The disadvantages of using station battery system for auxiliary d.c. voltage supply to static relays are the following :

— Voltage transients are introduced by opening of inductive circuits connected to the same battery supply (trip circuit for example). The voltage surges can damage the static relays. Hence special precautions are taken to design the static relays to absorb such transients (Ref. Ch. 43)

— The battery voltage is generally high, *e.g.* 250 V, this causes higher power loss in volt-ratio boxes used in static relays to get the reduced voltage.

To avoid these difficulties, the d.c. to d.c. converter is used. The station battery voltage is converted to a.c., then transformed and then rectified.

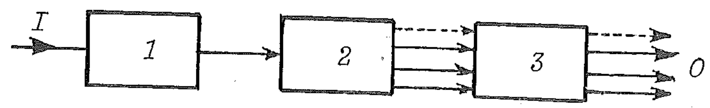


Fig. 38.42. Block-diagram of auxiliary d.c. voltage supply scheme.

1 — Input, d.c. voltage from station battery (d.c.)
1 — Inverted ; d.c. to a.c.
2 — Step-down transformer with required secondary voltages.
3 — Rectifiers, voltage regulators and smoothing circuits.
O — Output voltage for static relays (d.c.).

Fig. 38.42 illustrates the principle.

The d.c./a.c. converters are self-contained units. The voltages are converted generally from 220 V d.c. to about 50 V d.c. The converters are of enough ratings to supply the requirements of several relays.

In some cases, nickel-cadmium battery supplies are used for supplying static relays. These batteries are tricle changed from rectified a.c. source obtained from main potential transformers.

In some static relays, normal a.c. voltage is stepped down in the built-in auxiliary transformers in the relays, the rectified, established and smoothed.

38.37. FULL-WAVE RECTIFIER

Fig. 38.43 illustrates the circuit of a full-wave bridge rectifier having four diodes (1, 2, 3, 4) and input auxiliary transformer (5). When *A* is positive with respect to *B*, current flows through diodes 1 and 4. When *B* is positive with respect to *A* current flows through 2 and 3. In both cases, *C* is positive with respect to *D* and full wave rectification is achieved. The output contains ripple. To overcome this problem, smoothing circuit is necessary in the output.

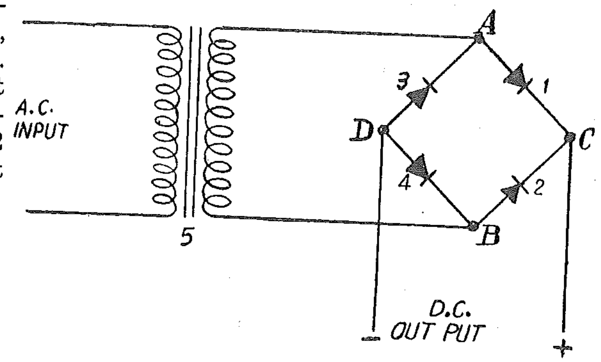


Fig. 38.43. Full-wave bridge rectifier.

38.38. SMOOTHING CIRCUITS

Smoothing circuit comprises reservoir capacitors, resistors, inductors. These are connected in output side of the rectifier. The process of charging the capacitors exponentially smooths the output waveform. The resistance determines the time-constant *RC*.

The voltage across the capacitor does not change instantaneously as capacitor requires finite time to get charged or discharged. Hence the voltage spikes or ripples get smoothened due to capacitor.

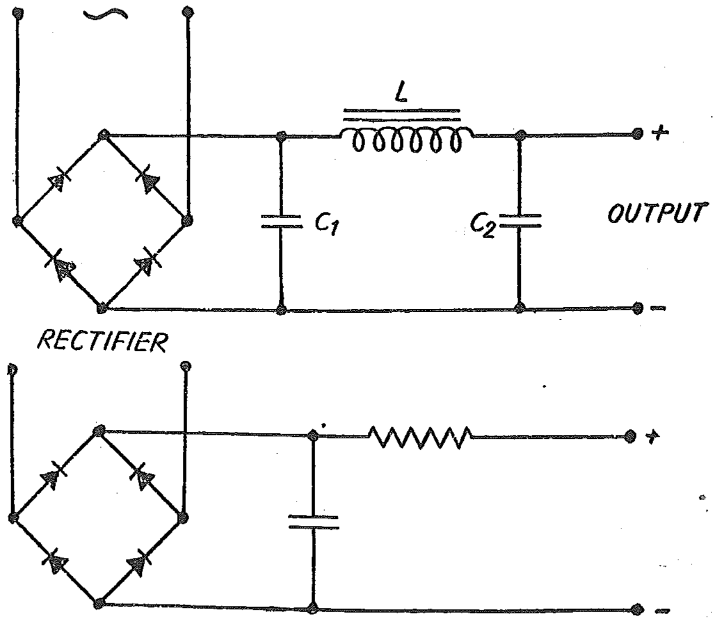


Fig. 38.44. Smoothing circuits in rectifier output side.

38.39. VOLTAGE STABILIZATION (REGULATION) BY ZENER DIODES

Zener diode is used for voltage stabilization. Fig. 38.45, illustrates the method of stabilizing the output voltage of a rectifier bridge by means of zener diode, zener diode is connected for reverse current flow. An improved stabilization is obtained by cascade connection of zener diodes.

The voltage across the zener diode remains constant over a wide range of current.

The bias of the input circuit (base-emitter) should be held constant. Zener **diodes** can be used for this purpose.

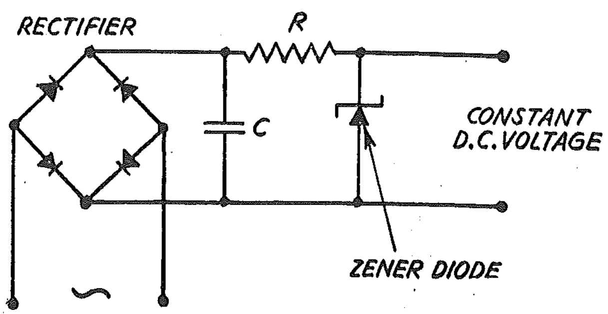


Fig. 38.45. Voltage stabilization by Zener diodes.

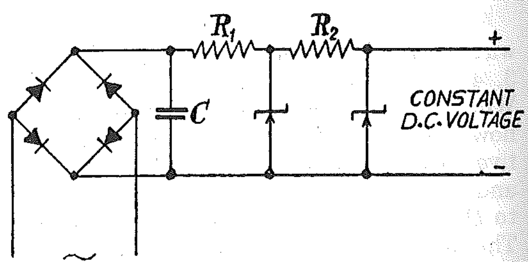


Fig. 38.46. Use of two zener diodes.

38.40. TIME-DELAY CIRCUITS

Time delay circuits are necessary in electronic circuits of static protection. These employ suitable combination of resistance and capacitance. The principle is as follows :

$$Q = CV$$

$$V = Q/C \text{(Ref. sec 3.2)}$$

$$= \frac{1}{C}\int i dt = \frac{1}{RC}\int V dt.$$

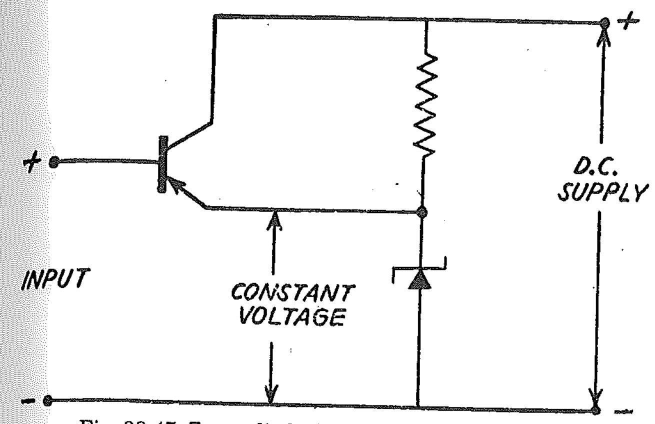


Fig. 38.47. Zener diode for voltage stabilization of input circuit.

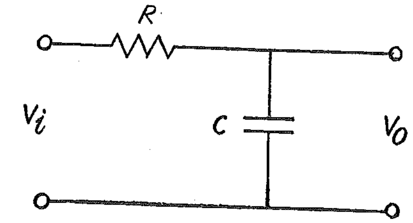


Fig. 38.48. Time circuit.

where T = Charging time of capacitor (From V_0 to V_i)

V_0 = Initial voltage across C

V_i = Final voltage across C, input voltage.

Consider Fig. 38.48. The capacitor is charged by the voltage V_i

The time is given by $T = RC \log_e \frac{V_i}{V_i - V_0}$

Delay Circuit

To achieve a very short delay of the order of a few micro-seconds delay line is used in Fig. 38.49.

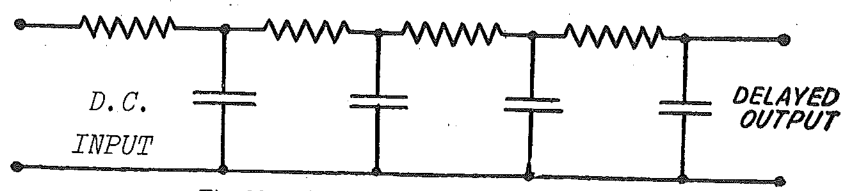


Fig. 38.49. Equivalent diagram of delay circuit.

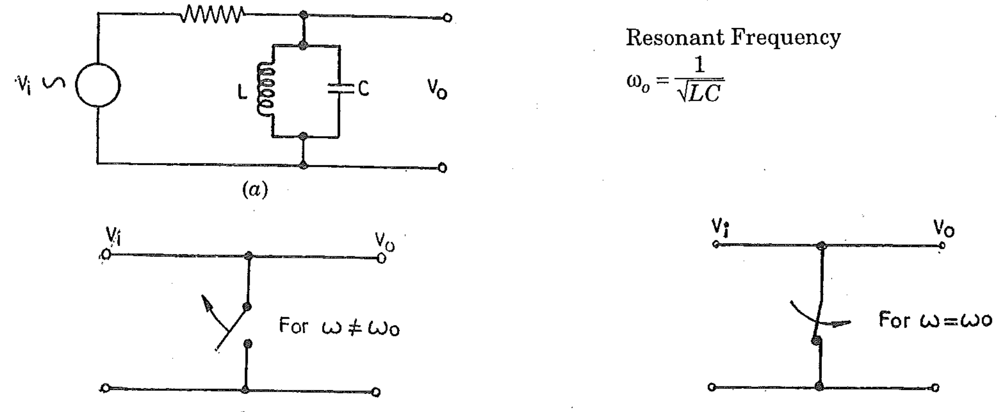
Time Delay Relay. For achieving intentional time delay in protection system, time delay relays are used. Time lags of 0.1 sec to several seconds can be adjusted in these (Details in Ch. 40).

38.41. FREQUENCY FILTERS

Filters are used for 'blocking' or attenuating certain frequencies and passing other frequencies.

Resonant circuits (turned circuits) are for passing of blocking the frequencies.

Parallel Resonant LC Circuit. (Fig. 38.50). The circuit having L and C in parallel with supply has a Resonant Frequency ω_0 at $\frac{1}{\sqrt{LC}}$. At resonant frequency, the impedance of parallel LC combination approaches zero. Thereby the voltage V_2 across output is reduced to zero. By judicious selection of L and C, the circuit can alternate/block frequencies from appearing across output (V_0).



Resonant Frequency

$$\omega_o = \frac{1}{\sqrt{LC}}$$

Fig. 38.50. Parallel LC circuit blocks resonant frequency ω_o and passes other frequencies.

Series Resonant Circuit (Fig. 38.51). It has series, R, L, C. At resonant frequency $\omega_0 = \frac{1}{\sqrt{LC}}$, the impedance of LC resonant circuit becomes zero. The resonant frequency is passed through the circuit. For other frequencies, the circuit offers higher impedance.

Band Pass Filter [Fig. 38.51 (*a*) and (*b*)]. A simple *RLC* filters discussed above are called passive filters.

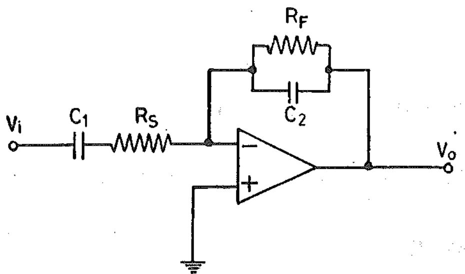
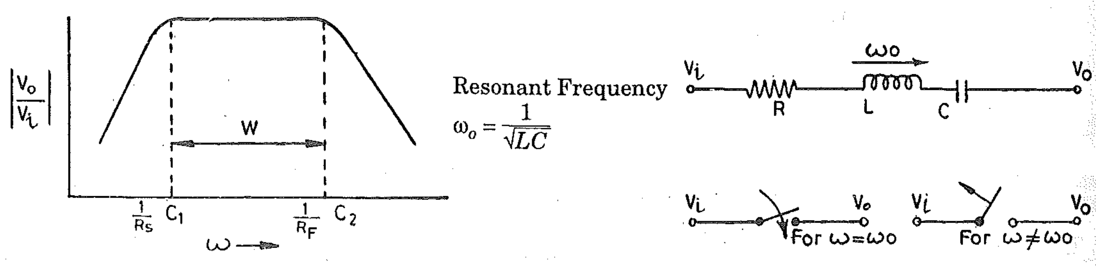


Fig. 38.51 (*a*). Band pass filter with operational amplifier, and its frequency response.

An active filter such as band pass filter con-



Resonant Frequency

$$\omega_o = \frac{1}{\sqrt{LC}}$$

Fig. 38.51. Series resonant circuit passes frequency ω_o and block other frequencies.

tains active element like operational amplifier and attenuates frequencies beyond its two limits and passes the frequencies within its band limits without attenuation [Ref. Fig. 38.51 (*b*)]

38.42. SYMMETRICAL COMPONENT FILTERS

The three phase vectors of an unbalanced system can be derived by vector sum of three sets of component balanced vector called positive sequence, negative sequence and zero sequence components (Ref. Ch. 21).

Symmetrical component filters are necessary to drive the symmetrical component (from output of CT's or VT's) for feeding into the comparator/level detector of static relay. For example in unbalance current protection, the negative phase sequence components is filtered and supplied to over-current relay (Ref. Sec. 31.7).

(*i*) **Negative Sequence Current Filter.** Negative sequence current filter is quite complex. Its design is complicated and expensive as it incorporates a trans-reactor (also called transactor). This is a special multi-winding CT having gapped core.

The secondary leads of main CT's are connected to the various primary terminal of trans-reactor (Transactor or Intermediate CT) is a required manner. The filtered output depends upon phase sequence of input connections. (If two of the input connections are interchanged, the negative sequence filter becomes positive sequence filter).

A simplified diagram of negative sequence filter is illustrated in Fig. 38.52 (*a*).

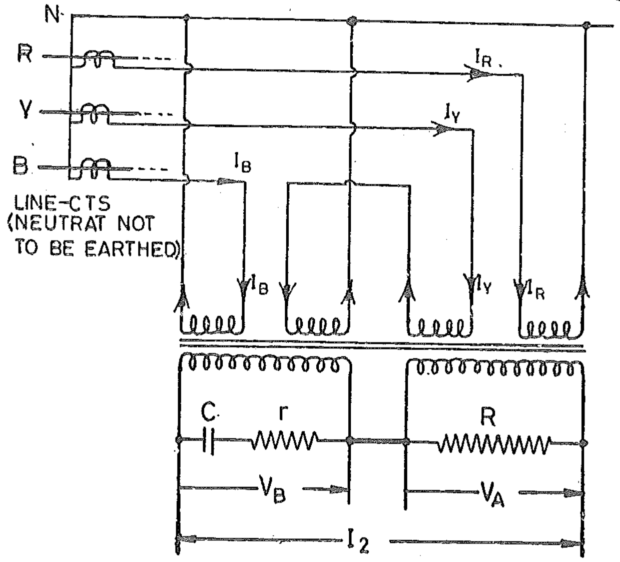


Fig. 38.52 (*a*). Negative sequence current filter.
– Circuit Diagram (Ref. Fig. 33.19, Sec. 33.11).

Fig. 38.52 (*b*) shows vector diagram for negative sequence condition (*YRB*) and Fig. 38.52 (*c*) give vector diagram for condition when only positive sequence condition (*RYB*) prevails.

The flux produced in the gapped-core of the transreactor due current $\bar{I}_R$ and $\bar{I}_Y$ is proportional to $\bar{I}_R - \bar{I}_B$ and $\bar{I}_B - \bar{I}_Y$. The resultant voltages depend upon the phase relations between V_A and V_B.

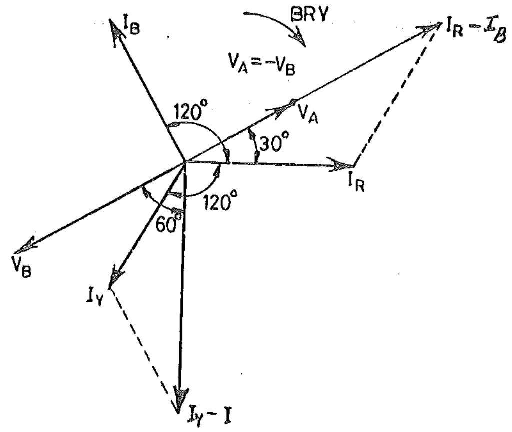


*Fig. 38.52 (*b*). Vector diagram for positive sequence condition of I_R, I_Y, I_B. V_B is equal and opposite to V_A.

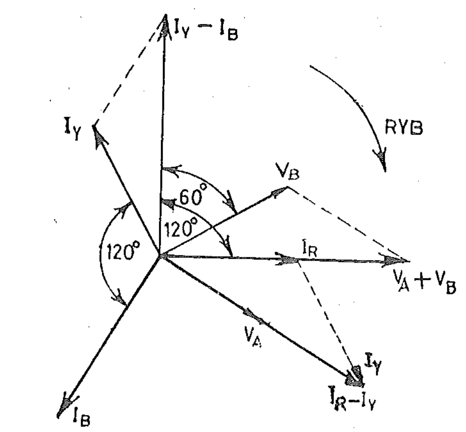


Fig. 38.52 (*c*). Vector diagram for negative phase sequence condition of I_Y, I_R, I_B, $V_A + V_B \neq 0$.

* Ref. Fig. 38.52 (*a*), when $V_A + V_B \neq 0$,
Negative sequence current output of the filter, $I_2 \neq 0$.

(*ii*) **Negative Sequence Voltage Filter.** Negative sequence voltage filter is connected to the secondary side of VT's. It passes Negative Sequence Component (V_2) the circuit voltage and rejects positive sequence and zero sequence components. The relay connected to the output side of negative sequence voltage filter respond to V_2 only.

For simplicity, the three input terminals of negative sequence filter are connected to line side having no zero sequence component (Star connection without earthing)

There are many possible methods of connecting r, L, C to get the filtered negative sequence output.

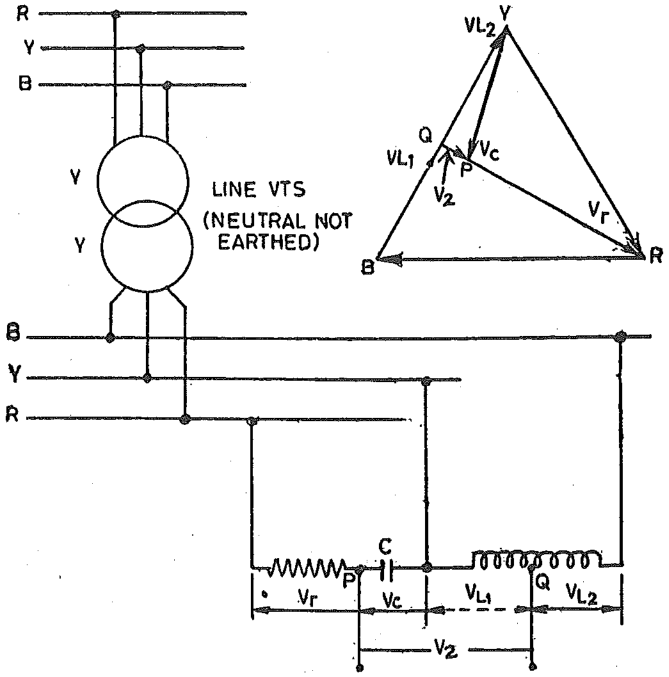


Fig. 38.53. Negative sequence voltage filter.

Consider Fig. 38.52 (*a*). For negative sequence condition of supply voltage (phase sequence YRB or when supply voltage contains negative sequence component) negative sequence voltage V_2 appears across *P*, *V*. When negative sequence component in line voltage is zero, the voltage V_2 is zero.

The same circuit can be used as a positive sequence filter by interchanging supply terminals.

39

Comparators and Level Detectors

Static Relay — Functional Circuits — Comparators — Amplitude Comparators — Rectifier Bridge Comparators — Phase Comparators — Pulse and Squared Input — Direct and Integrating Type Comparators — Integrating Amplitude Comparator — Hybrid Comparator Level Detectors — NPN Transistors — PNP Transistors — Operational Amplifier — Schmitt Trigger .

39.1. STATIC RELAY FUNCTIONAL CIRCUITS

The static relay unit comprises several functional circuits such as :

— input circuit with main CT's, Auxiliary CT's
— rectifiers smoothing circuits, filters
— level detector
— timer circuit
— filter circuit
— directional unit
— comparator
— amplifiers
— setting device
— starting relay
— output stage, etc.

The required functional circuits or units are connected in the final assembly.

Input stage

The input is derived from CT/PT. The output of CT/PT is connected to the auxiliary CT/PT. The input stage of a static relay comprise the following :

— CT's and or PT's.
— Auxiliary CT's or PT's.
— Summation units.
— Filter.

Rectifier and Smoothing Circuit

In single actuating quantity relays, the quantities are rectified in a single rectifier bridge. The output of the rectifier is smoothened to remove the ripple. The output is given to the level detector. Single actuating quantity relays include overcurrent relay, under voltage relay etc.

In double actuating quantity rectifier relay there are generally two rectifier bridges. The output of these bridges is compared. The output of the comparator is given to the measuring unit (level detector) after smoothing.

Comparator

Comparators receive the rectified inputs. After comparison the comparator output is given to the measuring unit.

There are several types of comparators such as amplitude comparator, phase comparator, hybrid comparators.

These are either direct (instantaneous) or integrating type.

Level Detector or Measuring Unit

This unit comprises a multi-stage feedback amplifier. The feedback ensure that for values of unit above a certain level, the output power increases in a step. Hence for input below threshold value, the level detector has no output. For input above threshold value, the output is obtained.

The measuring unit comprises logic circuits, amplifiers and level detector circuit. The logic elements determine the conditions of various input quantities for which output is obtained.

Amplifiers

The output of level detector is further amplified by amplifier. The amplifier strengthens the weaker signal. The output of the amplifier is given to the starting relay or output device.

Time-delay Element

The time-delay element is introduced between level detector and the amplifier. The time-delay can be adjusted by changing R-C combinations.

Output Stage

The output stage of static relay may have one of the following :

— electromagnetic relay such as permanent magnet moving coil relay.

— thyristor in series with trip coil and auxiliary switch.

The operation of the complete relay is a team-work of these functional blocks. The manufacturers supply variety of relays of the same type but having certain modifications to suit particular applications by putting together required functional blocks. For example, a time-delay unit is added to get time delay; volt-ratio box may be added to permit selection of auxiliary supply voltage; output stage may have an electromagnetic relay or a thyristorized trip. Hence, the relay assembly is built up of various blocks, each serving certain specific function. Such blocks are called functional components of static relays. The study of static relays is simplified by studying these functional components first and then the block-diagram of various relays.

Each functional component is built up from discrete components such as resistors, diodes, transistors, capacitors, etc. Some of the components, are soldered on a printed circuit of glass-fibre reinforced expoxi-laminate or the functional component is made up of an integrated circuit. The printed circuit card (or integrated circuit with its connections) together with other components of the relay such as transformers, switches potentiometers, etc. are mounted on a relay base plate.

Alternatively each functional component may be an IC or a group of functional components may be formed on a single IC.

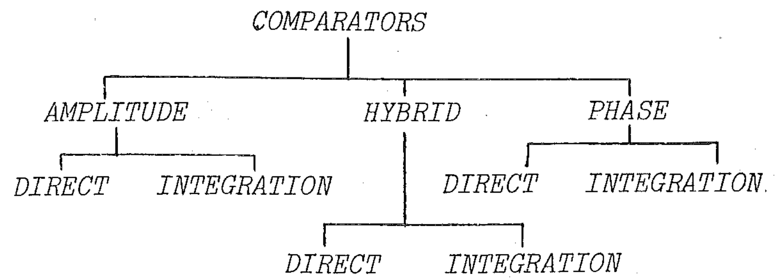
PART I. COMPARATORS

39.2. COMPARATORS

In double actuating quantity relays, two quantities are compared.

For example in circulating current differential protection (Ref. Ch. 28) the current entering in the protected zone (I_1) and current leaving the protected zone (I_2) *are compared.* In phase comparison type carrier current protection type carrier current protection (Ch. 30) the phase angle between signals from sending end and receiving end are compared. In distance relays the ratio of vector V and vector I are compared. These are some examples of comparison studied earlier.

Table 39.1



Comparator is a part of relays which receives two or more inputs to be compared and gives output based on their comparison.

Comparators can be broadly classified as — (1) Amplitude comparator (2) Phase comparator (3) Hybrid comparator.

Comparators are either direct (instantaneous) type or integrating type. In integrating type comparator the output of the comparator is integrated with respect to time. (Ref. Table 39.1.).

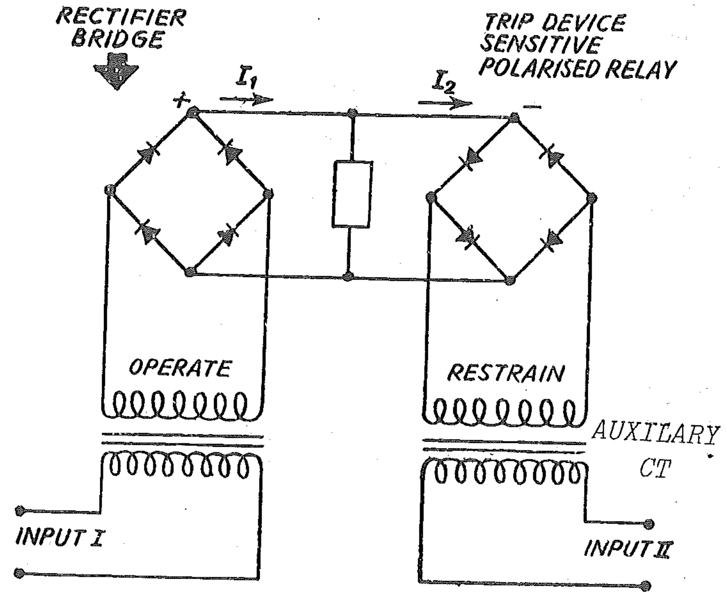


Fig. 39.1. Amplitude comparator circulating current circuit with two inputs.

Multi-input comparators are either single phase or poly-phase, can employ either amplitude or phase comparison or both. In general case of multiple operating inputs and multiple restraining inputs, the operation is governed by an equation.

$$|S_{01}| + |S_{02}| + |S_{03}| \ldots > |S_{r1}| + |S_{r2}| + \ldots$$

where left hand side gives total operating input and right hand side gives total restraining input.

Hybrid type comparator combines the amplitude comparator and phase comparator.

39.3. AMPLITUDE COMPARATORS

Amplitude comparator compares the magnitude of the two (or more) input, quantities. The phase angle between the two (or more) inputs is not recognised or noticed by the amplitude comparator.

Consider two vectors $\bar{A}$ and $\bar{B}$. It compares the magnitude of these inputs *i.e.*, $|A|$ and $|B|$. The comparator receives two inputs and gives output is the algebraic difference between magnitudes, *i.e.* $|A| - |B|$.

The function of amplitude comparator is illustrated in Fig. 39.2.

Symbol $|A|$ denotes the magnitude of complex function A.

The output $|A| - |B|$ of comparator is :

Positive if	$|A| > |B|$
Negative if	$|A| < |B|$
Zero if	$|A| = |B|$

In some cases the comparator compares the two magnitudes by 'Ratio'. The output of the comparator $|A|/|B|$ is :

greater than 1 if	$|A| > |B|$
less than 1 if	$|A| < |B|$
zero	$|A| = 0.$

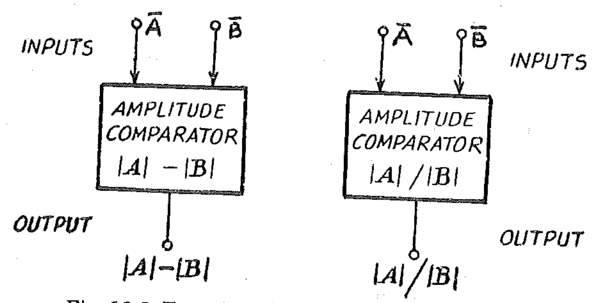


Fig. 39.2. Function of amplitude comparators.

The amplitude comparators are generally in the form of :

Rectifier Bridge Comparators. The input quantities to static relays is either in the form of sinusoidal current derived from main CT or sinusoidal voltage derived from PT. CT or PT give analogous output, faithful to the main circuit quantity.

Each input quantity is given to one full-wave rectifier bridge.

Two full-wave rectifier bridges are connected in opposition and the output relay is connected in parallel to the two rectifier bridges. The output of the rectifier bridge comparator is received by the output stage continuously.

Fig. 38.3 (*a*) illustrates the configuration and Fig. 39.3 (*b*) illustrates the waveforms. The output stage receives continuously a direct current equivalent to $|I_1| - |I_2|$.

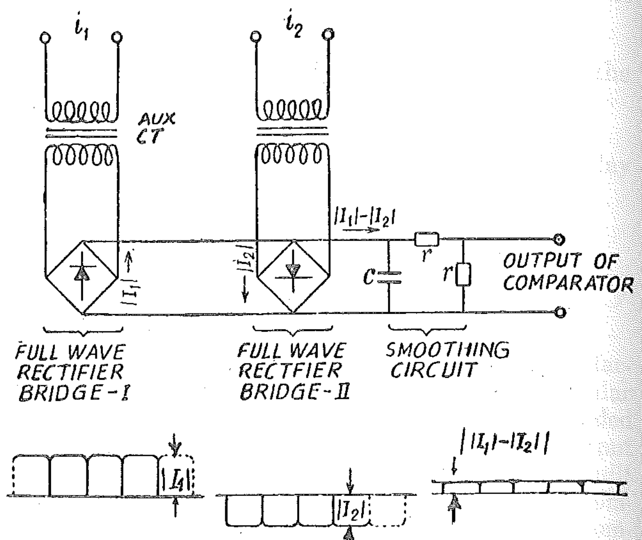


Fig. 39.3. Amplitude comparator formed by rectifier bridges.

The output stage is rectifier bridge comparators can have one of the following devices :

— Permanent Magnet Moving Cost Relay

— Sensitive Polarised Relay

— Static Integrator.

When $|I_1| - |I_2|$ exceeds the threshold value, the stage acts and the relay picks-up.

39.4. PHASE COMPARATORS

Phase comparators compare the two (or more) input quantities vectorially. The phase comparators recognised the vector (both magnitude/phase) relationship between the inputs. A vector $\bar{A}$ has magnitude $|A|$ and phase angle say, α. There are two kinds of phase comparators.

(*i*).Phase comparator which recognises only phase angle between input waveforms.

If ϕ is phase angle between vector $\bar{A}$ and $\bar{B}$, the output of phase comparator depends on angle ϕ and the relay responds to the phase angle ϕ between the two inputs.

(*ii*) Phase comparator which recognises the vector product (or division) between two (or more) input quantities.

Thus a phase comparator has output $\bar{A}, \bar{B}$ or $\bar{A}/\bar{B}$.

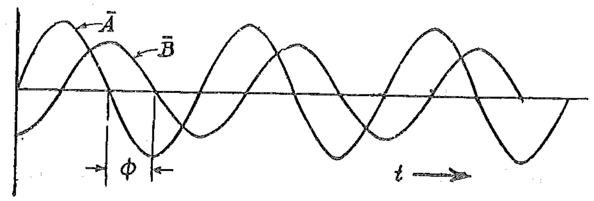
39.5. PHASE COMPARATOR BASED ON RECTANGULAR (OR SQUARED) PULSES

Ref. Fig. 39.4. Suppose the sinusoidal analogous input waveforms $\bar{A}$ and $\bar{B}$ are converted into rectangular waveforms [*A*] and [*B*] before feeding to Phase Comparator.

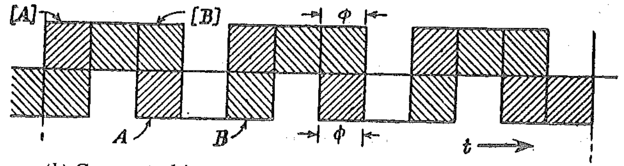
The magnitude of the input waveform may be disregarded and the comparator recognises only phase angle ϕ in this type of phase comparator.

The rectangular waveform [*A*] is in phase with sinusoidal waveform *A*. Similarly [*B*] in phase with $\bar{B}$.

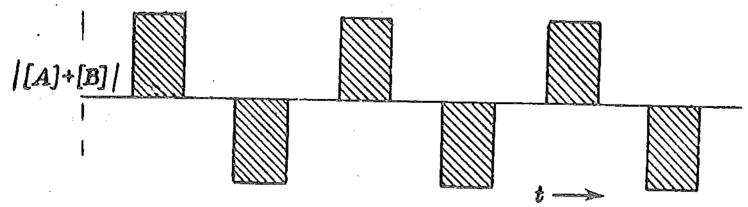
The comparator receives the rectangular waveforms [*A*] and [*B*]. The resultant waveforms of [*A*] + [*B*] and [*A*] – [*B*] are illustrated in Fig. 39.4 (*c*) and (*d*)



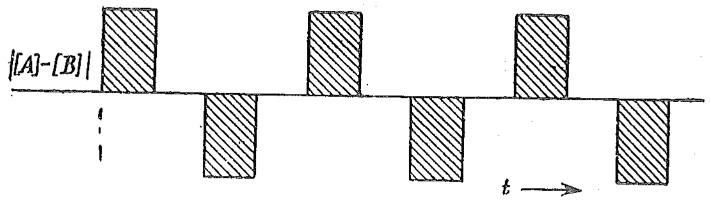
(*a*) Input waveforms (Analogue) at phase angle $\phi = 90°$.



(*b*) Converted into equivalent rectangular waveforms.



(c) Pulses of [*A*] + [*B*]



(*d*) Pulses of $|[A] - [B]|$ for $\phi = 90°$.

Fig. 39.4. Use of rectangular inputs in phase comparators.

For, $\phi = 0$ $\quad |[A]+[B]| = |[A] - [B]|$

$\phi < 90°$ $\quad |[A]+[B]| > |[A] - [B]|$

$\phi > 90°$ $\quad |[A]+[B]| < |[A] - [B]|$.

Thus, if the comparator circuit is arranged to measure the difference

$$|[A] + [B] - |[A] - [B]||,$$

the phase angle between $\bar{A}$ and $\bar{B}$ can be predicted.

The output of the phase comparator is in terms of magnitude.

The other possibilities of phase comparators adopting other techniques (such as phase split inputs, coincidance circuits) are described later. Such comparators can bed readily adopted with logic circuits and are useful in modern relays.

39.6. PHASE COMPARATORS BASED ON VECTOR PRODUCT DEVICES

The vector product devices (such as Hall Effect Generator Ref. Sec. 38.12). Have an output (e_o) given by, say,

$$e_o = AB \sin \phi$$

where A = r.m.s. value of input 1,

B = r.m.s. value of input 2

ϕ = phase angle between 1, 2.

This phase comparator is basically analogue device and cannot be readily adopted in logic circuits.

39.7. DIRECT (INSTANTANEOUS) AND INTEGRATING TYPE COMPARATORS

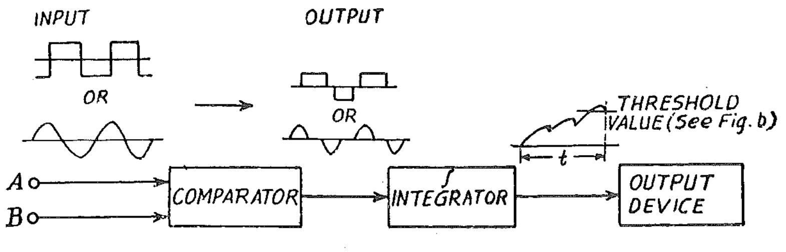
Comparators (Phase or Amplitude) can be either Direct Type of Integrating Type.

In Direct Comparator the 'period' or 'time' of comparison is not recognised. Hence time aspect is not international. (The comparator may have inherent response time).

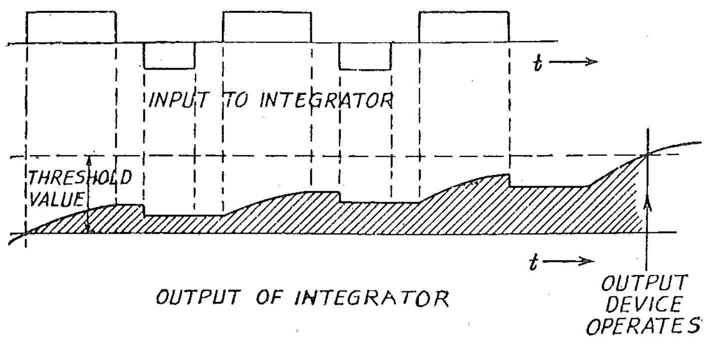
The output of comparator corresponds to the comparison of inputs at *every instant.*

In integrating type comparator, the quantity (generally output) of the comparator is integrated with respect to time. When the integrated output reaches a threshold value the output device operates.

Ref. Fig. 39.5. Two rectangular equivalent inputs are given to comparator. Comparator output $[(A) - (B)]$ is given to integrator.



(*a*) Function of integrator.



(*b*) Details of waveform of integrator input and output.
Fig. 39.5. Integrating Comparator.

(Ref. Sec. 38.24). The integrator generally has a capacitor which gets charged as shown in Fig. 39.5 (*b*). The voltage across the capacitor increases with positive pulse and its duration and decreases with negative pulse and duration. The settings are such that under normal conditions in main circuit, the positive pulses and negative pulses received by the integrator are such that its output does not reach the threshold value. Hence output relay remains open. When the integrator output reaches threshold value, the output device operates.

In Fig. 39.5, square inputs are illustrated. In some other comparators, input are be sinusoidal or triangular.

39.8. INTEGRATING AMPLITUDE COMPARATOR

Fig. 39.6 illustrates the integrating type of amplitude comparator.

The two sinusoidal inputs A and B are given to the input of comparator (*a*). The output $|A - B|$ waveform (*b*) is supplied to the shaper. The shaper converts into equivalent square pulses

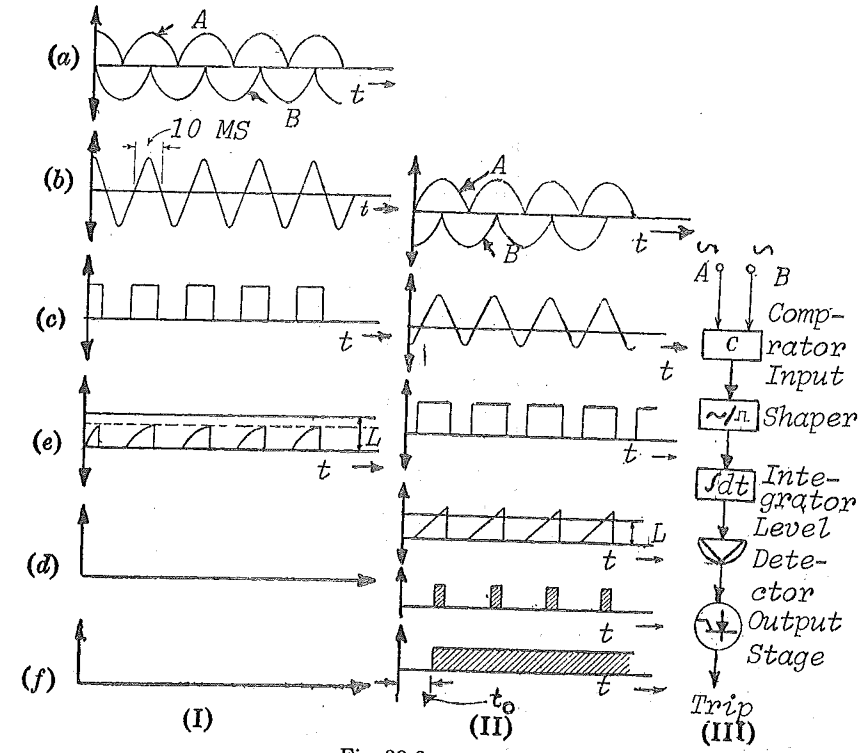


Fig. 39.6.

(*c*). These pulses are given to integrator. The integrator output depends upon duration and magnitude of input square pulses. At the beginning of every pulse, the capacitor in the integrator starts getting charged. When $A > B$ (as shown in II), the triangular output of integrator (*d*) increases above the setting of the level detector (L).

When $A < B$, the level detector does not give any output [I-*e*].

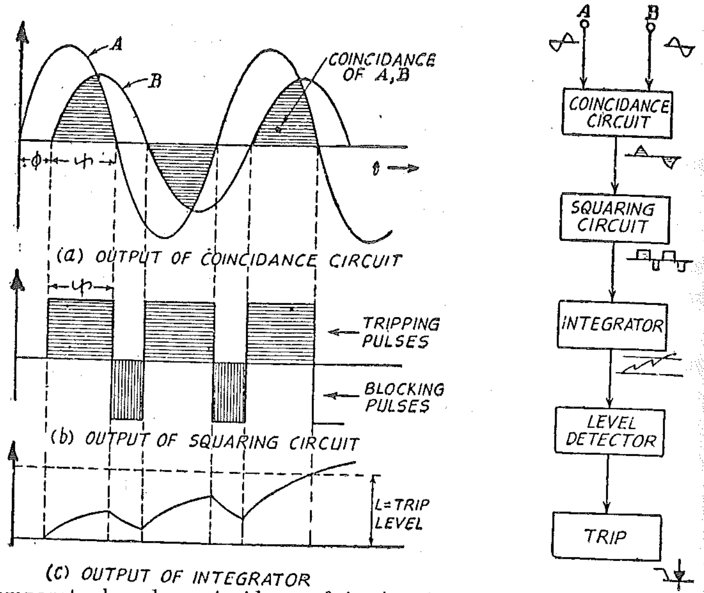
When $A > B$, the level detector gives output [II-*e*] and trip current flows.

39.9. OPERATING TIME

Suppose $A = B$ as shown in Fig. 39.6-I, before fault in main circuit (not shown). At $t = 0$, fault develops in main circuit and $A > B$ (Fig. 39.6-II). The time required for trip current to start flowing is indicated in Fig. 39.6-II f by t_o. It is the time required by integrator to charge its capacitor. It is of the order of 5 ms. Further time of about 2 ms is required for operation of output stage. Hence the relay time can be minimised to 10 ms ± 3, *i.e.* $\frac{1}{2}$ cycle.

39.10. COINCIDENCE TECHNIQUES IN PHASE COMPARATORS

Fig. 39.7 illustrates the principle of a phase comparator based on coincidence of sinusoidal inputs. Coincidence denotes overlapping of the two signals. Referring to Fig. 39.7 (*a*), the sinusoidal inputs A and B overlap during the period ϕ. The hatched portion in Fig. (*a*) indicates coincidence. The coincidence circuit has output during this period ϕ. This output is converted into squares in the squaring circuit. The output of squaring circuit is supplied to integrator. The output of the integrator is given to level detector with setting L. The pulse are integrated in integrator. When the output of integrator Fig. 39.7 (*c*) exceeds level detector setting L, the level detector gives signal to output stage. The thyristor in output stage is thereby triggered.



Output of integrator touches Level l, when $p = 90$ (balance) Tip occurs for $\phi = 90°$.

Fig. 39.7. Phase comparator based on coincidence of sine inputs.

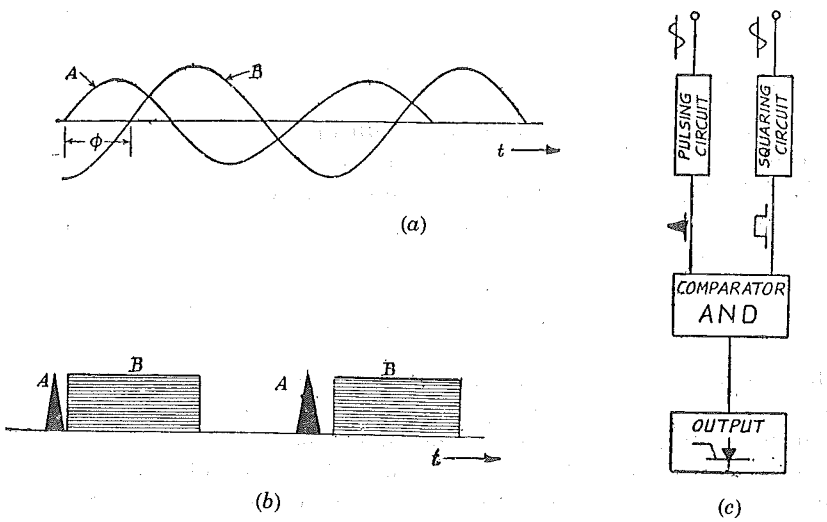
If period ϕ of coincidence between A and B is

(*i*) less than 90°, relay does not operate as the output of integrator always remains below L.

(*ii*) more than 90°, relay operates as the output of the integrator exceeds L.

39.11. SPIKES AND BLOCK COINCIDENCE TECHNIQUE IN PHASE COMPARATOR

Ref. Fig. 39.8. Inputs A and B are sinusoidal. Input A is converted into a spike in a pulsing device. Input B is converted into rectangular blocks in squaring circuit. The converted pulses are shown in Fig. 39.8 (*b*).



(Spike and block not coincident, the output of AND is zero, relay does not operate)

Fig. 39.8. Coincidence phase comparator with spike and block technique.

The spikes and blocks are supplied to an AND gate [Fig. 39.8 (*c*)]. The AND gates gives output when both the rectangular block and the spike coincide.

39.12. PHASE COMPARATOR WITH PHASE SPLITTING TECHNIQUE

Fig. 39.9 illustrates this method in which both the inputs A and B are split into two components A, A and $B, B\ \angle 45°$. Thus totally four input signals are received by the comparator. The comparator is an AND gate which gives output when all the four inputs are simultaneously positive or negative.

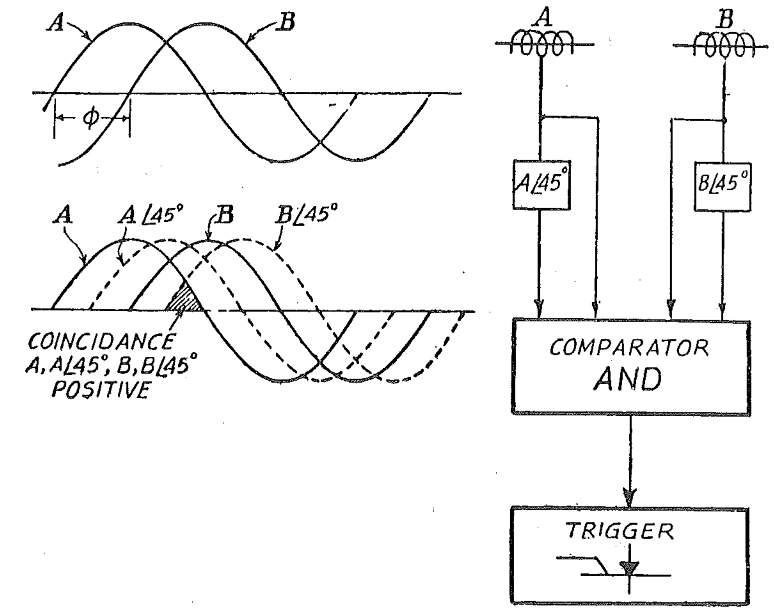


Fig. 39.9. Coincidence phase comparator with phase splitting technique.

The coincidence of all four signals is possible when the phase angle ϕ between A and B satisfies the condition.

$$90° > \phi < -90°$$

39.13. HYBRID COMPARATOR

Hybrid comparator compares both magnitude and phase of the input quantities. It is a Hybrid (mixed version) of amplitude and phase types.

Ref. Fig. 39.10. The inputs are given to a phase comparator. The output of phase comparator is given to Amplitude Comparator. The output stage follows.

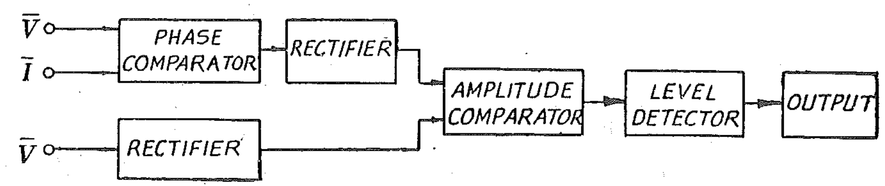


Fig. 39.10. Hybrid comparator (incorporating phase comparator and amplitude comparator) used in a distance relay.

The static impedance relays which compare V and I are generally hybrid comparators. Variety of impedance diagrams (rectangular elliptical) etc. are possible with Hybrid Comparators.

Section II. LEVEL DETECTORS

39.14. LEVEL DETECTOR

A level detector is a functional circuit in a protective relay which determine the level of its inputs with reference to a predetermined setting. Ref. 39.11. When the inputs (*I*) exceed the level (*L*) the output (*O*) of the level detector exceeds and the output stage of the relay gets a triggering signal *via* an amplifier.

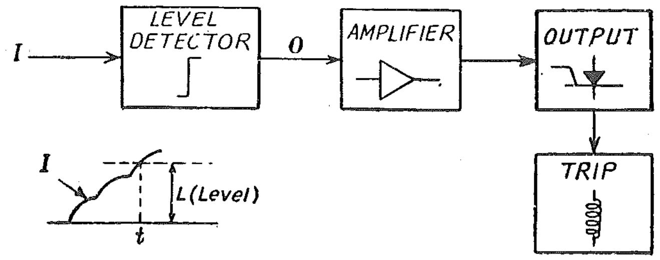


Fig. 39.11. Explaining level detector (when input *l* exceeds level *L*, the output *O* increases).

When input (*I*) is below a certain level, the output is negligibly small.

An Analogue Level detector with operational Amplifier has been described in Sec. 38.15.10. Some other simple circuits are described here.

39.15. LEVEL DETECTOR BY PNP TRANSISTOR

Referring to Fig. 39.12, the input to level detector V_i should have desired level to make the PNP transistor conducting. The base should be negative with respect to emitter. Therefore, base

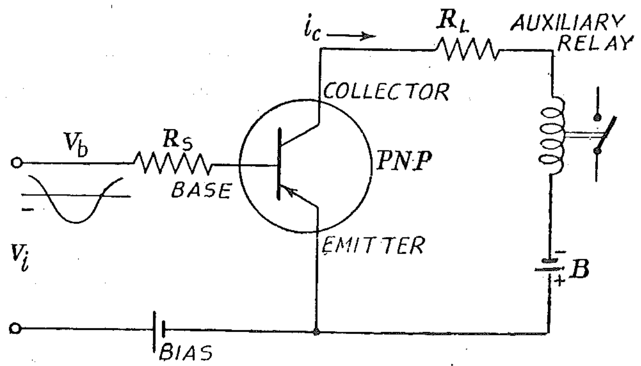


Fig. 39.12 (*a*). Simple level detector with PNP transistor. (When Base of PNP transistor gets a negative voltage with respect to collector, the transistor is turned on).

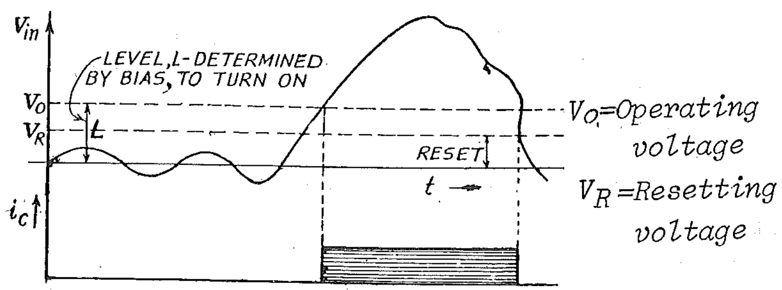


Fig. 39.12 (*b*). Operation of transistor in Fig. 39.12 (*a*).

to emitter voltage (negative) should exceed the positive bias. When the base voltage V_b reaches level *L* determined by the bias, the transistor is turned on. The current i_b flows from battery *B* through emitter, collector, auxiliary permanent magnet moving coil relay. When base to emitter voltage V_b is below threshold level (0.6 *V* silicon transistor) current i_c is zero.

39.16. NPN TRANSISTOR AS LEVEL DETECTOR

Consider the common emitter connection of a NPN transistor (Fig. 39.13). When base to emitter voltage is negative or less than the threshold value no substantial emitter current can flow. When the base to emitter voltage is positive and exceeds the threshold value the transistor is turned on, current i_c flows through collector (and load). I_c is of the order of milliamperes.

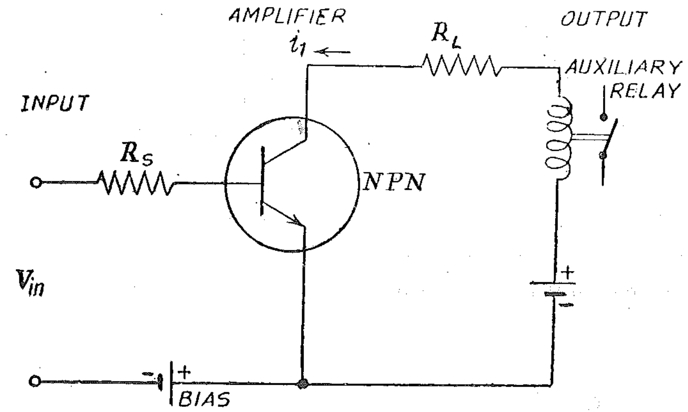


Fig. 39.13. NPN Transistor as level detector.

39.17. SCHMITT TRIGGER WITH OPERATIONAL AMPLIFIER

Ref. Sec 38.24 for application of operational amplifier as a level detector. The circuits shown in Figs. 38.36 and 38.37 are with negative feedback. (Feedback applied to negative terminal of operational amplifier) Negative feedback is generally necessary in feedback control systems for stabilization. However in protective relays negative feedback is generally not necessary and positive feedback is preferred.

In positive feedback, the output is applied to the positive terminal of the operational amplifier. When the operational amplifier is turned into ON state, it remains in ON state till the operating quantity is reduced to below reset level.

Ref. Fig. 39.14, since feedback is positive, the output V_0 is either equal to $+V_{CC}$ or $-V_{CC}$ depending upon the history of the waveform (Hysteresis). Follow the waveform of input in Fig. 39.14 (*c*). When input reaches $+V_{CC}/2$, the output changes its state from $+V_{CC}$ to $-V_{CC}$ and remains at that level till V_i reaches $-V_{CC}/2$.

A sinusoidal input V_i gives a square wave output V_O Schmitt Trigger can be used as a level detector. When input reaches V_{CC}, the output changes its state.

V_0	V_i	V_i *for* $(R_1 = R_2)$
$+V_{CC}$	$V_s < \frac{R_2}{R_1+R_2} V_{CC}$	$V_s < V_{CC}/2$
$-V_{CC}$	$V_s > \frac{R_2}{R_1+R_2} V_{CC}$	$V_s > -V_{CC}/2$

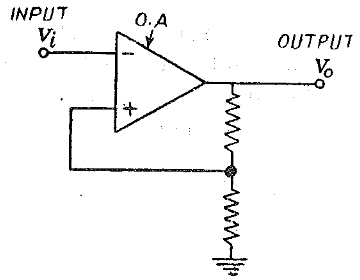


Fig. 39.14 (*b*). Schmitt Trigger with O.A.

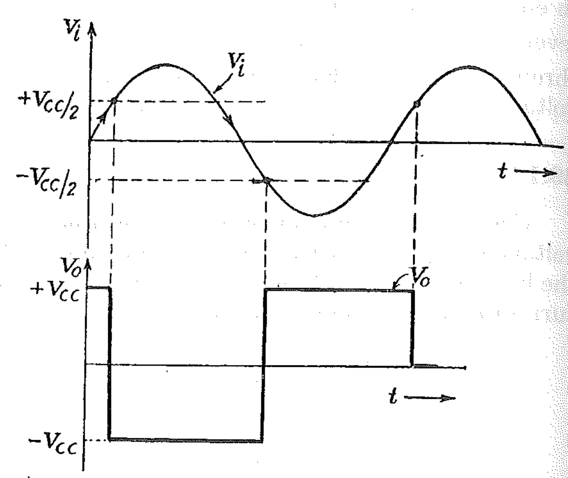


Fig. 39.14 (*c*). Waveforms of V_i and V_0 for $R_1 = R_2$.

39.18. SCHMITT TRIGGER WITH TWO NPN TRANSISTOR

Ref. Fig. 39.15. Transistor Q_1 is normally not-conducting and Q_2 conducting. The potential of base B_2 of transistor Q_2 is determined by the supply voltage V_s and values of resistors R_1, R_2, R_3. Because voltage V_s across supply and ground gets divided across R_1, R_2, R_3 in proportion to their resistances.

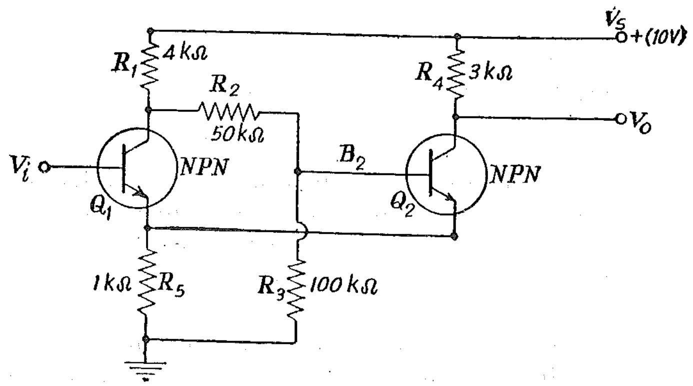


Fig. 39.15 (*a*). Schmitt trigger circuit with two NPN transistors.

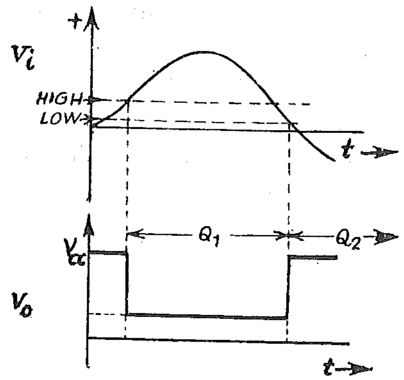


Fig. 39.15 (*b*). Waveform of (*a*).

When V_i reaches threshold value (High) and is positive, Q_1 is turned ON. Current diverts to Q_1 · Q_1 is saturated thereby potential of B_2 is dropped below reset value.

Q_2 stops conducting. Thereby the output voltage V_o increases to V_s.

When V_i becomes low (0.6 V for silicon) Q_1 stops conducting and Q_2 starts conducting and driven into saturation. The voltage V_s gets divided across R_4, R_5, and V_0 reduces to low value.

QUESTIONS

1. State the various functional circuits in a static relay with the help of block diagrams. Explain the function of various blocks.
2. Describe the functions of Amplitude Comparator and Phase Comparator. Explain the difference between Direct and Integrating type Amplitude Comparators with the aid of illustrated waveforms.
3. Explain the circuit of an integrating type of phase comparator by means of block diagram and waveforms.
4. Explain the phase comparison technique based on (1) spike and block inputs (2) phase splitting. Illustrate with the help of block diagrams and waveforms.
5. Explain the following :
   — phase splitting technique used in Integrating Type Phase Comparator.
   — use of AND gate in phase comparators.
6. Explain the function of Rectifier Bridge comparator used as amplitude comparator.
7. Illustrate block diagram of an integrating type amplitude comparator having two current inputs having phase difference ϕ.
8. State the function of level detector. Explain the use of Schmitt Trigger circuit as a level Detector. What is the advantage of positive feedback?
9. Write short notes on any two :
   1. Schmitt Trigger with Transistors Level Detector.
   2. Integrating Type phase comparators.
   3. PNP as Level Detector.
   4. Schmitt Trigger with Operational Amplifiers as Level Detector.
   5. Rectifier Bridge comparator Relay.

40

Static Overcurrent Relays

Advantages — Single Actuating Quantity Relays, Double Actuating Quantity Relays — Instantaneous Overcurrent Relays — Timing Circuit — Time Delay Overcurrent Relays — Directional Overcurrent Relays — Block Diagrams — Summary.

40.1. INTRODUCTION TO STATIC OVERCURRENT RELAYS

The applications of conventional electromagnetic overcurrent relays have been discussed in Ch. 27. The conventional electromagnetic overcurrent relays are at present commonly used in many applications. However, static overcurrent relays offer several advantages such as :

— Reduced VA consumption (7 m VA to 100 m VA) as compared with electromagnetic relays (1000 m VA to 3000 m VA). Therefore the performance of CT under short-circuit condition is improved. The size of CT core is also reduced.

— Static relays are compact. The size of a single three phase overcurrent relay may be about one-fourth of three electromagnetic relays.

— Static overcurrent relay is not affected by vibrations.

— The static relays can have more accurate time-current characteristic.

— Static overcurrent relays can be of following types.

Overcurrent relay without time lag.

Overcurrent relay with time lag.

Directional overcurrent relay with time lag.

The applications of these relays have been discussed in Ch. 27.

The static overcurrent relay has generally the following functional blocks. (Ref. Sec. 391.1)

— *input circuit* comprising Main CT, auxiliary CT, current setting switch RC Filter.

— *rectifier* with smoothing circuit (Ref. Ch. 39)

— *level detector* (Ref. Ch. 39)

— *amplifier* (Ref. Ch. 38)

— tripping relay (Ref. Ch. 38)

In overcurrent time delay relays a time delay circuit is added between the rectifier and level detector to achieve desired time characteristic.

The overcurrent relays without directional feature are as a rule single actuating quantity relays. The directional overcurrent relays are as a rule double actuating quantity relays, the direction of power flow is sensed by sensing the phase angle between current and voltage.

The various functional blocks mentioned above are standardised by the manufacturer. Depending upon the type of relay, the required functional blocks are connected in the final assembly.

40.2. SINGLE ACTUATING QUANTITY RELAYS

A brief description of rectifier relays has been given in Sec. 26.14.

The protective relays at either single actuating quantity relays such as overcurrent, under-voltage, earth fault relay or double actuating quantity relays such as distance relay, differential relay. Fig. 40.1 given a simplified block diagram of a single actuating quantity rectified current relay.

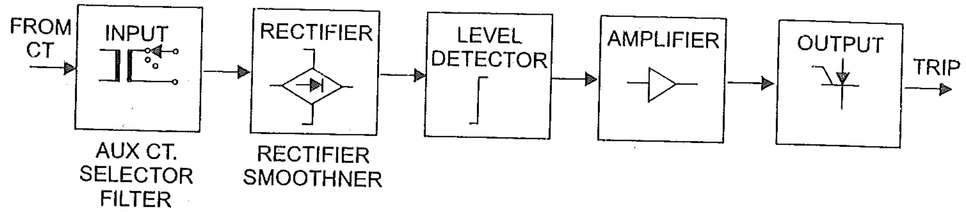


Fig. 40.1. Simplified block-diagram of a single actuating quantity.

The secondaries of CT's are connected to a summation circuit (not shown). The output of the summation circuit is given to the intermediate current transformer. The output of the current transformer is supplied to full wave rectifier bridge. The rectified output is given to *measuring element* (level detector). The measuring element determines whether the quantity has reached the threshold value or not. The measuring element detects the level of the input signal. The measuring element can be one of the following three types :

— moving coil permanent magnet relay — polarised moving iron relay

— static relay

In some cases the output of the rectifier is amplified and fed to electromechanical relay.

The static measuring element comprises d.c. amplifiers with transistors. The amplifier is single stage, two-stage or three stage and is usually feedback type. The feedback ensures progressive rise of output power when the input to the measuring unit reaches a certain level.

When input to measuring unit is less than threshold input, the output of the level detector is zero. For an overcurrent relay,

for $I_{in} < I_{th}$, $I_{out} = 0$

for $I_{in} > I_{th}$, $I_{out} =$ Present

where, I_{in} = Input to measuring unit

I_{out} = Output of measuring unit.

I_{th} = Threshold value of input.

In an actual, relay, I_{th} can be adjusted.

After operation of the measuring element (level detector) the output of the level-detector is amplified by amplifier.

The amplified output is given to the output device. The trip coil of the circuit-breaker is connected in the output stage.

If time-delay is desired, a timing circuit is introduced before the level detector.

Smoothing circuit (Ref. Sec. 34.13) and filters are introduced in the output of the rectifier.

The above mentioned description applies to a static overcurrent relay. The protection operates if $I_{in} > I_{th}$ with a set time delay. Static overcurrent relay is made in form of a single unit in which transistors, diodes, resistors, capacitors etc. are arranged on printed board and are bolted with epoxy resin.

40.3. DOUBLE ACTUATING QUANTITY RELAYS (Ref. Sec. 26.14)

In distance relays, differential relays, directional relays, etc. two quantities are fed into the measuring unit. Fig. 40.2 gives a block diagram of a double actuating quantity rectifier relay.

The outputs of *CT*/*PT* are fed to summation units. The output of summation unit is rectified and fed to comparator. When the output of comparator increases to a certain value the output of level detector is initiated.

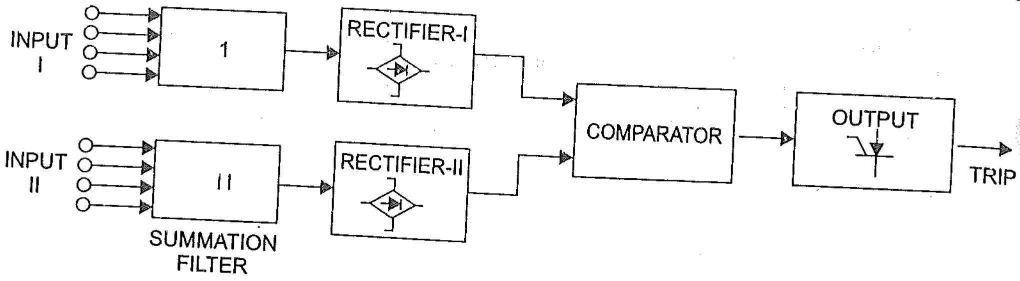


Fig. 40.2. Block diagram of a double actuating quantity relay. Level detector and amplifier not shown Refer (Fig. 40.1 above).

In Fig. 40.2, Level detector and Amplifier blocks (between comparator and output) are not shown for simplicity.

40.4. BASIC PRINCIPLE OF STATIC OVERCURRENT RELAYS

Figs. 40.1, and 40.3 illustrate simplified functional blocks in a single actuating quantity static overcurrent relays. The blocks diagrams of complete relay are given in Fig. sec. 40.8 and 40.9.

Ref. Fig. 40.3. The secondary current of line CT is generally not suitable for static relay operations. It is higher. The line CT may be selected with a suitable higher current ratio (such as 4000/5).The intermediate CT (Auxiliary CT) reduces the current further to 1 Amp. so that it is suitable for static relay circuits. The input Functional Block comprises the following :

— Auxiliary CT (Ref. 35.15)
— Current detector
— Filter for suppressing harmonics (Ref. sec. 38.31)
— Spike suppressor for protecting static relays from over-voltage spikes which are harmful to the relay components.

The desired current range can be selected by setting the tap at desired position. The alternating current derived from auxiliary CT may contain harmonics particularly under short-circuit condition. The high voltage spikes in the waveform are harmful to the semi-conductor devices in static relays. Hence, filters and spike suppressors are provided in the input stage of the static relay.

The current rectified in fullwave rectifier and is smoothened (Ref. Sec. 38.27 and Sec. 38.28) in smoothing circuit comprising resistors and capacitor. The smoothing circuit eliminates the ripple in the output waveform of the rectifier. The output of rectifier is proportional to the r.m.s. value of input a.c. waveform.

The output of rectifier is supplied to level detector (Ref. Sec. 39.13 to Sec. 39.16).

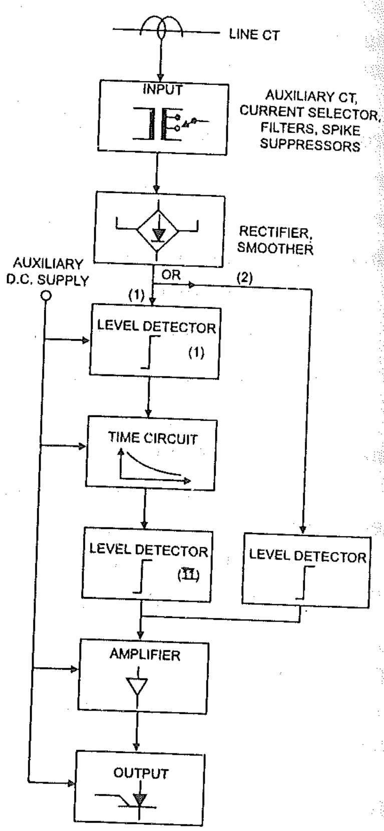


Fig. 40.3. Block diagram of static overcurrent relay (1) with time delay. (2) without time delay block.

In instantaneous overcurrent relay without intentional time delay. (Ref. Definition in Sec. 25.8) time delay functional block is not necessary. In instantaneous relays, the output of rectifier is given to level detector and then to amplifier (Route 2 Fig. 40.3).

In time overcurrent relay, the rectifier output is supplied to level detector (I) and a timing circuit is added in between the level detector (I) and level detector (II). Route 1. Fig. 40.3.

The output of level detector is amplified in Amplifier. The output of amplifier is given to output stage of static relay. The amplifier amplifies the signals from level detector.

The output of static overcurrent relay may be any of the following :

— moving coil permanent magnet d.c. relay.
— thyristor in series with trip coil (Ref. Sec. 38.7.5.).

The auxiliary d.c. supply is necessary for level detectors, amplifiers output stage of static relay.

In single actuating quantity relay, comparators are generally not necessary.

40.5. TIME CHARACTERISTIC

We will recall that the time characteristic of a protective overcurrent relay is plotted with operating quantity (current) on x-axis and operating time on y-axis. (Ref. Sec. 27.4, Fig. 27.2) the details described in this section may please be referred).

The general equation for time characteristic is given by

$$I^n \, t = K$$

where I = Current sensed by relay
k = Constant
t = Time of operation
n = Characteristic index of relay

In conventional electromagnetic relays, n can vary from 2 to 8. Let us consider three possibilities on n.

(i) With $n = 0$

$$I^{\circ} \, t = K$$
$$t = K$$

The characteristic is a straight line parallel to current axis.

It is known as definite characteristic.

(ii) With $n = 1$

$$It = K$$

The characteristic is called inverse characteristic.

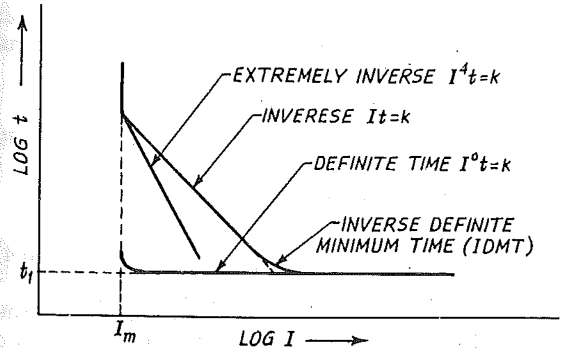


Fig. 40.4. Time characteristics of overcurrent relays.

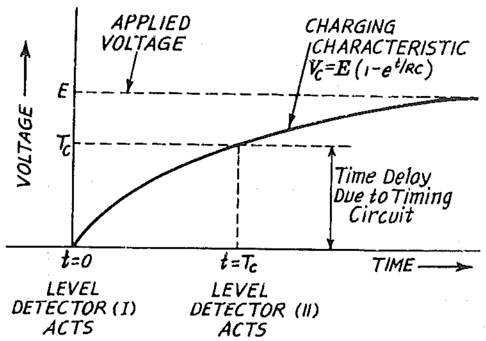


Fig. 40.5. Characteristics of time circuit.

(iii) With $n = 8$, the characteristic becomes extremely inverse.

Instantaneous characteristic with conventional electromagnetic relays can have approximate time of the order of 0.1 second. However in static overcurrent relays instantaneous overcurrent relays can be with half cycle or one cycle operating time. (10 to 20 ms).

The general expression for operating time of a time-circuit relays can also be expressed as,

$$t = \frac{KM}{I^n - I_p^n}$$

where
I = Tap current multiplier
I_p = Multiple of tap current at which pick-occurs.
K = Design constant of the relay.
M = Time Multiple setting.

In the above expression if the relay picks up at tap-current, *i.e.* $I_p = 1$, then

$$= \frac{KM}{I^n - 1}$$

The static overcurrent time relays can have the following typical characteristics :

IDMT standard inverse :

$$t = \frac{0.15}{I^{0.20} - 1}$$

Vary inverse : $t = \frac{14}{I} - 1$

Extremely inverse : $t = \frac{70}{I^2 - 1}$

The same relay can be given different characteristics by changing its components.

40.6. TIMING CIRCUIT

When d.c. e.m.f. (E) is applied to a capacitor, the voltage across the capacitor (V) does not increase instantaneously. Initially it is zero. The voltage increases exponentially, given by

$$V_c = E\left(1 - e^{-\frac{1}{RC}}\right) \quad ...(40.3)$$

where
E = d.c.e.m.f.
V_c = Voltage across capacitor
$RC = \tau$ = Time constant of RC circuit where R is Thevenins equivalent resistance viewed from capacitance. (Ref. Fig. 40.6)

at $t = 0$, when e.m.f. is applied.

$V_c = E\,(1 - e^{-0}) = 0$

at $t = \tau$, time constant

$V_c = E\,(1 - e^{-1})$

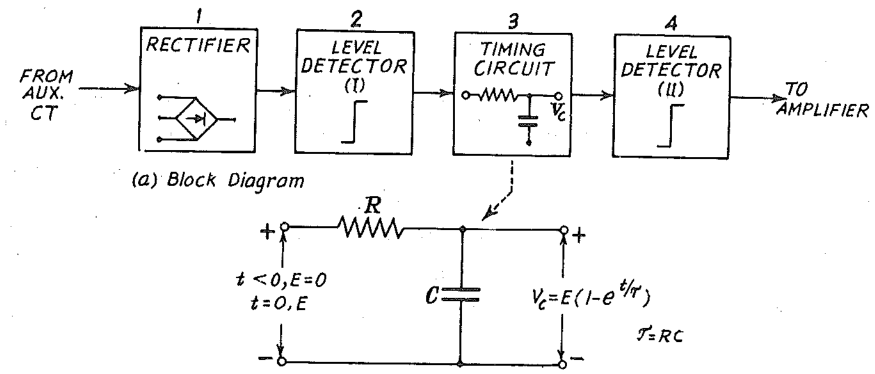
$= E\left(\frac{e-1}{e}\right)$

The charging time from $t = 0$ at $V_c = 0$ to $t = T_c$ at $V_c = V_t$ is given by

$$T_c = RC \log_e\left[\frac{E}{E - V_t}\right] \quad ...(40.4)$$

Consider timing circuit (Fig. 40.6). When the output of rectifier reaches a threshold value, the level detector (I) gives output ray E · (at $t = 0$). Before $t = 0$, the output of level detector (1) zero and there is no input to timer. As the level detector (2) acts voltage E is applied to timer. The capacitor starts getting charged. The voltage V_c increases exponentially. Suppose V_T is the threshold value of the level detector (4). Time required to reach this voltage depends upon time for charging the capacitor C given by,

$$T_c = RC \log_e\left[\frac{E}{E - V_T}\right] \quad ...(40.5)$$

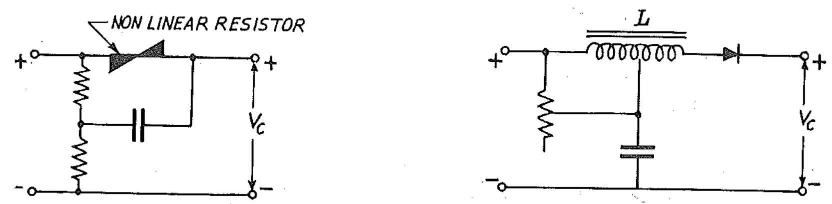


(*b*) Timing circuit of Block 3.

Fig. 40.6. Function of timing circuit in overcurrent time relay. (Ref. Fig. 40.5).

Hence time delay given by the time delay circuit is given by the above expression. By varying values of R, C the time can be varied without difficulties. The basic R, C circuit can be also arranged in several series parallel combinations to charge equivalent value R and τ.

Non-linear resistors are used to get other time characteristics (Ref. Fig. 40.7).



(*a*) Timing circuit with non-linear resistor. (*b*) Timing circuit with diode.

Fig. 40.7. Some forms of timing circuits.

Instantaneous Characteristic

The time delay circuit containing C is omitted from the block diagram. Such a circuit would need only one level detector. As there is no moving parts operating times of the order of 1 cycle can be achieved in static relays.

Applications

Time delay overcurrent relays are used in overcurrent protection of utility equipment, distribution circuits, protection of generators, motors, transformers etc. Instantaneous overcurrent relays are used for short circuit protection of large equipment.

Instantaneous overcurrent relays are also useful in other protective relay systems. (Ref. Ch. 27).

40.7. DIRECTIONAL OVERCURRENT RELAY

(Please Ref. Sec. 27.11 -Directional overcurrent protection.)

Directional relay senses direction of power flow by means of phase angle between V and I. When this angle exceeds certain predetermined value, the directional relay operates with a condition that the current is above in pick-up value. Hence directional relay is a double actuating quantity relay (Fig. 40.2) with one input as current I from CT and the other input as voltage V from VT.

With the electromagnetic directional overcurrent relays, discrimination is affected when voltage drops down (under fault condition) for faults very close to the location of VT. With static directional overcurrent relays, this voltage drop does not cause a problem.

Because the static comparators used in directional overcurrent relay can be made sensitive to voltage and static directional overcurrent relays can give reliable performance upto 1% of system voltage.

Block Diagram

Ref. Fig. 40.8. The directional overcurrent relay has two inputs (*I* and *V*). The inputs are supplied to phase comparator. A phase shifter is added in voltage input circuit before supplying it to phase comparator to achieve maximum output of phase comparators under phase faults/earth fault condition.

The output of phase comparator is given to level detector and then to amplifier.

If time delay is necessary, a timer is added in the block diagram.

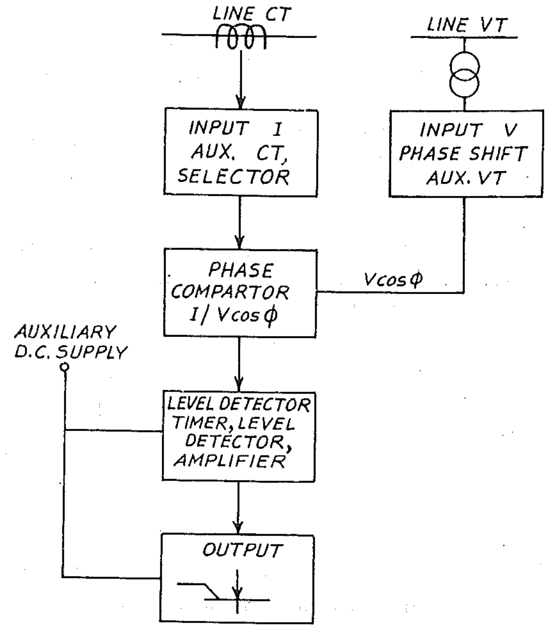


Fig. 40.8. Simplified block diagram of static directional overcurrent relay.

Directional Units for Directional Overcurrent Relays

The choice of directional unit depends upon the type of comparator. (Ref. Ch. 39). The comparator used in directional overcurrent relay may be one of the following :

1. *Hall Effect* generator (Ref. Sec. 38.12).
2. Rectifier bridge comparator (Ref. Sec. 38.12, 39.2).
3. Instantaneous coincidence comparator (Ref. Sec. 39.9).
4. Integrating coincidence phase comparator (Ref. Sec. 39.10).

Block Diagram Development

With the earlier background we can develop the Block Diagram for the following. It will be an interesting and useful exercise.

Example 40.1. *Develop Block Diagrams of following relays indicating the functional blocks from input to output stages. Describe the function of each block and the basic principle of its circuit. Indicate the auxiliary d.c. supply, line CT and VT.*

1. Static overcurrent relay
2. Static overcurrent time delay relay.
3. Static directional overcurrent relay without time delay.
4. Static directional overcurrent relay with time delay.

The student may compare his block diagrams with some of the following diagrams.

40.8. STATIC INSTANTANEOUS A.C. MEASURING RELAYS

Courtesy : ASEA, Sweden.

(A) General

Static instantaneous a.c. measuring relays include instantaneous overcurrent relay, instantaneous under-current, instantaneous over-voltage relay and instantaneous under-voltage relay. The application include high-set instantaneous over-current protection of motors, transformers, feeders, distribution lines; under-voltage protection of busbars feeding several motors, etc. Instantaneous protection is provided where time-lag is not desirable and differential protection is not justified economically. Static instantaneous a.c. relays have the following important features :

— Measuring circuits built-up of static components.
— Setting of maximum and minimum values (over/under) in the same relay.
— Wide scale range, with ratio 1 : 3
— Stepless setting of operating values
— High resetting ratio.
$\geq$ 95% for maximum operation
$\geq$ 105% for minimum operation
— Low power consumption, current relay : 0.3 m VA
Voltage relay : 20 m VA
— Standard current relay completely insensitive to d.c. components.
— High resistance of shocks and vibrations due to absence of moving parts.
— Auxiliary voltage stabilization provided with the relay.
— Compact.

(B) Principle of Operation

The block-diagram Fig. 40.9 explains the functional arrangement in a static current-under-current relay. The auxiliary-input transformer shown in the figure, is connected to the secondary of main current transformer (not shown). The input transformer has an air gap (except those for extremely low power consumption). The functions of various static components are described in Ch. 34. The relay can be fed from auxiliary voltage such as 24 V, 48-60 V, 110-125 V, 220-250 V d.c. Resistor ratio box is provided internally.

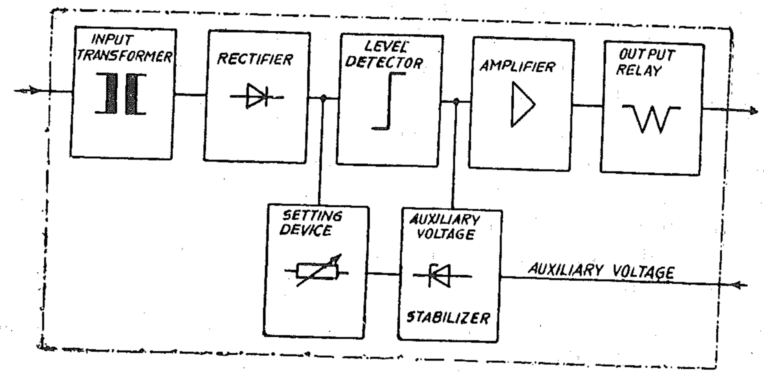


Fig. 40.9. Block diagram of static instantaneous overcurrent/under-current relay.

The rectified input is compared with a quantity derived from stabilized auxiliary reference voltage. The difference is fed to the level detector. When the input quantity reaches a certain threshold condition, the level detector detects the condition and gives output. The same is amplified so as to operate the auxiliary relay in the output stage.

(C) Technical Data on Static Instantaneous Current Relay and Instantaneous Voltage Relay

— Maximum voltage between line 500 V a.c.

— Rated frequency : 50 to 60 Hz

— Power consumption at lowest setting

Current relay : Measuring circuit : 7 m VA to 100 mVA auxiliary voltage circuit : 2 to 4 W

Voltage relay : Measuring circuit : 20 m VA auxiliary voltage circuit : 2 to 4 W

— Temperatures permitted : – 5°C to + 50°C

— Impules test : according to BEAMA 219

— Power frequency test : 2000 V, 50 Hz, 1 sec.

— Operating time : 30 to 55 m sec.

40.9. STATIC TIME-LAG OVER-CURRENT RELAYS

(A) Applications

Static over-current time-lag relays can be used for short circuit protection of generators, transformers, motors and also in simple supply networks at medium-distribution voltages. When combined with directional relays the over-current relays can be used for directional overcurrent protection of simple inter-connected systems. They can also be used as starting elements, in conjunction with longitudinal differential relays for protection of lines. The designs, include both inverse time-lag and independent time lag design, for use in single phase of three phase systems.

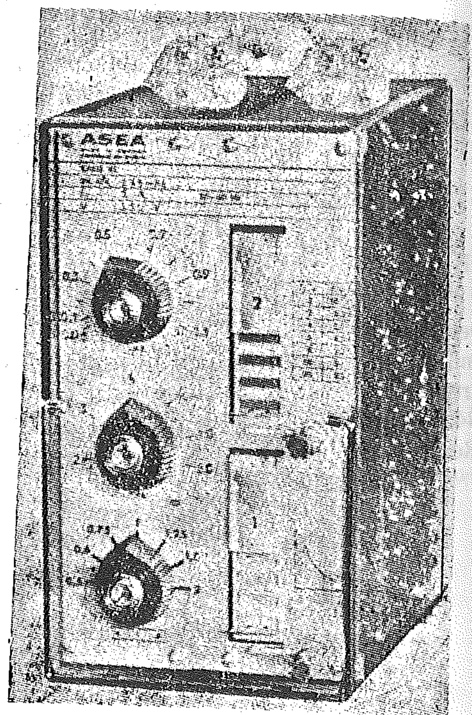


Fig. 40.10. Time-lag-over current relay.

(B) Design and Principle of Operation

[*Courtesy* : ASEA, Sweden]

The block diagram (Fig. 40.11) explains the circuit of a time-lag overcurrent relay developed and marketed by ASEA, Sweden. The applications of the relay are mentioned above. The relay has a built-in input current-transformer with several taps on secondary. Current setting can be obtained by selecting the tap.

From the switch for setting the operating current, a voltage connection is taken across resistor. The voltage is rectified, smoothed and compared with reference voltage. When the former voltage exceeds the reference voltage, the starting relay picks-up. At the same time, the *RC* circuit starts charging up.

The method of charging depends upon the type of relay. The charging in case of independent time lag relay is done from stabilized voltage. For a relay with inverse time lag characteristics, the charging is done by voltage proportional to current.

The inverse characteristics, in case of inverse-time-lag relays are obtained through combination of zener diodes, resistor employed in *RC* circuits.

When the capacitor in RC circuit charges up to a certain voltage level, the tripping relay pick-up.

In three phase design, the measuring circuit acquires voltage proportional to the largest of the three-currents.

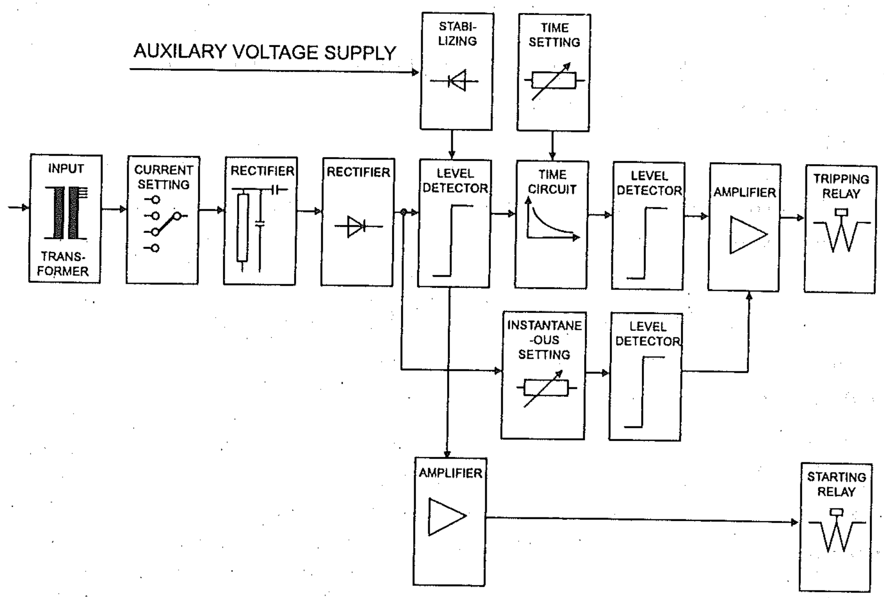


Fig. 40.11. Block diagram of static-time lag-overcurrent relay.
[*Courtesy* : ASEA, Sweden.]

Instantaneous operation is obtained through part of the voltage rectified from the transformer, being compared with reference voltage and when the latter is exceeded, an operational impulse is given to the tripping relay. Inductor flags are provided for both starting and tripping relays and are actuated by armature on corresponding output relay.

(C) Current Setting

The current setting is selected by turning a knob in the front of the relays thereby selecting the tap on secondary of input transformer. Typical example : Current scale for current setting graduated at 0.5, 0.6, 0.75, 1, 1.25, 1.5, 2, which multiplied by scale constant 1, 2, 4 or 8 A gives four current ranges 0.5 — 2, 1 — 4, 2 — 8, 4 — 16 A.

(D) Time Setting

The knob for time setting gives time multipliers. Thus if the time required from the graph or table is say 4 seconds for time multiplier of 1, then time will be $0.8 \times 4 = 3.2$ seconds for time setting of 0.8.

(E) Instantaneous Operation

Instantaneous operation is independent of d.c. component in short circuit current.

(F) Starting Operation

The contacts of starting relay can be utilized for :

Instantaneous tripping following by high speed auto-reclosure and delayed tripping.

Blocking of other relays in the event of overcurrents.

Blocking protection of radial fed busbars, transformers, cables.

Operating counters for recording number of faults which have not led to tripping.

Actuating separate indicating devices.

(G) Maintenance

Under normal condition, the relay requires no special maintenance. Burnt contacts on output relay should be carefully dressed with diamond file or extremely fine file.

Characteristics

The basic relay types offer variety of characteristics mentioned below :

— Extremely Inverse : BS 142 : 1966
— Very Inverse : "
— Normally Inverse : "
— Independent time lag : 0.2 — 2 s.
— Independent time lag : 0.6 — 6 s.

Voltage Ratings

Auxiliary d.c. voltages for various types : 24 V, 36, 48-55, 110, 125, 220, 250 V d.c.

Current Ratings

1 A in scale 0.2 02A
2 A in scale 1 — 4 A
5 A in scale 2 — 8 A
Frequency : 50-60 Hz.

Some Technical Data

Instantaneous operation, time : 50ms.
Starting operation, time : 20 ms.
Overshoot time : < 60 ms.

Power Consumption of Measuring Circuit

Rated current	*Power consumption at rated current*
1 A	0.02 — 0.07 VA
2	0.03 — 0.0 VA
5	0.05 — 0.13 VA

40.10. STATIC DIRECTIONAL RELAY

[*Courtesy* : ASEA, Sweden]

(A) General

Directional relay is double actuating quantity relay and senses phase angle between the two actuating quantities.

Let the phase angle between the current and voltage supplied to the relay be ϕ whilst the characteristic angle be α. When ϕ is equal to α, the relay has maximum sensitivity. This means that the relay operates when the supplied current I is as large as the set value I_s on the scale. For other values of I_s the relay operates when I, cos $(\phi - \alpha) \geq I_s$. The angles are used in the formula with their signs and accordingly the angle ϕ is then negative for a capacitive phase displacement.

In three-phase systems, the operation of the relay is also determined by an angle β which is that angle between the phase voltage to which the current is related and that voltage supplied to the relay. Since the angle is positive when the current lags the phase voltage, the relay operates when $I \cos(\phi - \alpha + \beta) \geq I_s$.

When the relay is connected for 60° and 90° angles of phase displacement connection will mean that cos $(\phi\ \alpha + \beta) = 1$ when the angle = 60° or 90°, the relay thus obtaining maximum sensitivity.

The reactive power Q has a phase-displacement of 90° in relationship to the active power P. It leads P when the phase displacement is inductive and is, therefore, positive.

Abbreviations

$U-$ = D.C. voltage
$U_\sim$ = A.C. voltage
U_n = Rated voltage
I_s = Set current
I = Current supplied to the relay
α = Characteristic angle of the relay
ϕ = Angle between current and voltage to the relay
β = Angle between the phase voltage to which the current is related and that voltage supplied to the relay.
ϕ_k = Angle between current and voltage to the relay at short-circuits.
P.F. = Power factor
P = Active power
Q = Reactive power.

Functional Circuit of a Directional Relay

The relay mainly comprised one current and one voltage transformer, a potentiometer, a converter, a smoothing circuit, a level detector with an amplifier and an electro-magnetic output relay, see Fig. 40.12. The current and voltage transformers, the potentiometer and the output relay are mounted individually, whilst the other components are on a printed-circuit board. The components together form a plug-in unit which occupies four relay seats in the plug-in system. The characteristic angles – 30° and – 90° are obtained by a capacitor in the voltage circuit, the angle + 65° being obtained by a capacitor in both the voltage and the current circuit.

As is apparent from Fig. 40.12 the current and voltage are fed *via* a phase shifting capacitor and transformers to a converter. The converter consists of two rectifier bridges and a resistor across which an average voltage value is extracted and supplied to the smoothing capacitor and the level detector.

The rectifier bridges are connected to the voltage transformer and the current transformer in such a manner that they pass conductive alternatively. In this way, a current is allowed to form the centre tapping of the current transformer through the resistor and rectifier bridge which is conductive at the time.

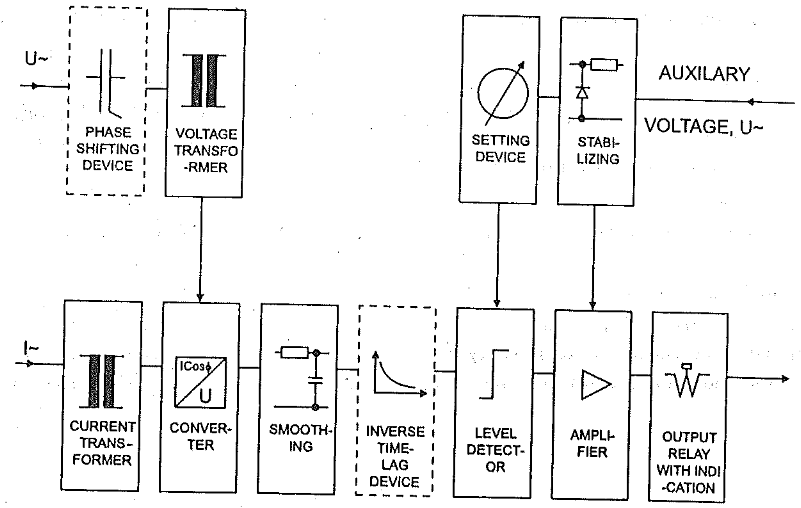


Fig. 40.12. Block diagram of a static directional relay.
[*Courtesy* : ASEA, Sweden.]

When $\phi = \alpha$ at the current flows through the resistor in the same direction the whole time and the average value of the voltage across the resistor, which is proportional to $I \cos (\phi - \alpha)$, thus provides maximum sensitivity, *i.e.* the relay operates for a current of the same value as the set value I_s.

The larger the difference between ϕ and α the smaller the average value of the voltage through the resistance will be at a constant current I. For a 0° difference, the average value will be zero irrespective of the value of the current.

The voltage over the resistor is smoothed fed to a transistorized level detector provided with an amplifier. By increasing the time constant in the smoothing circuit, it is possible to obtain a delayed operation with an inverse characteristic. The auxiliary voltage for the level detector and thus the operating value of the relay set by means of a potentiometer at the front of the relay. When operating, the amplifier feeds a voltage to the output relay which pick up, the indicating flag then becomes visible.

Summary

Static overcurrent relays have less burden compared electromagnet relays. They are compact and can give wide range of characteristics.

Basic static overcurrent relay has following functional blocks :

Input, Rectifier, Level detector, Amplifier, Output (Tripping).

In case of time lag overcurrent relay, an additional Time Delay Block is necessary.

Directional overcurrent relay, is basically double actuating quantity relay. It receives current input from CT and voltage input from VT. The rectified inputs are supplied to comparator. The comparator output is given to integrator or time delay circuit. The directional overcurrent relay can be instantaneous type of integrating type.

Static overcurrent relay circuit comprises the required functional blocks.

QUESTIONS

1. With the help of neat block diagram, explain the functioning of a static overcurrent relay without time delay. Explain function of each block.
2. Describe the circuit of a Directional Overcurrent Relay. Explain with the help of waveforms and block diagrams the use of integrating type coincidence phase comparator for directional overcurrent relay.
3. (*a*) Explain the principle of *RC* time delay circuit.

   Describe the use of such time delay circuit in a overcurrent time delay relay with the help of block diagram.

   (*b*) Explain the terms Inverse IDMT, Instantaneous overcurrent characteristics.
4. In a static relay, when the level detector operates, a voltage of 100 V DC applied across *RC* circuit having $R = 12$ kΩ, $C = 1$ μF. Calculate time taken for the voltage across capacitor to reach threshold value of 60 V after operation of the level-detector.

   (**Hint.** Ref. Eqn. 39.5)
5. With the help of neat block diagram, explain the functioning of static overcurrent directional time delay relay.
6. Write short notes on any three :
   — Time delay circuits in static relay — Directional overcurrent relay
   — Time characteristics of static relays — Instantaneous overcurrent relay.
7. Write short note on merits of static overcurrent relay compared with electromagnetic overcurrent relay.

41

Static Differential Protection of Power Transformers

Introduction — Merits — Differential Protection of two winding Transformers — Three Winding Transformer — Inrush Proof Quantities — Technical Data — Summary

41.1. INTRODUCTION

The principle of differential protection was described in Ch. 28. Their application to protection of power transformer generator and station bus was covered in Ch. 32, 33 and 34. We will recall that the *differential protection responds to vector difference between two or more similar electrical quantities.* In differential protection, current transformer secondaries are connected in such a way that under internal fault condition, the out of balance secondary current flows through the operating coil of the relay. 'Bias'or 'Restraint' is provided to prevent maloperation during external faults and inrush currents. *This principle is applicable even for static differential relays. In static differential relays the two (or more) similar input quantities are compared in static comparators, usually the rectifier bridge comparators.* This gives wider flexibility in relay design regarding characteristic and range.

This differential relay measures the vector difference between two similar electrical quantities say voltage/voltage or current/current.

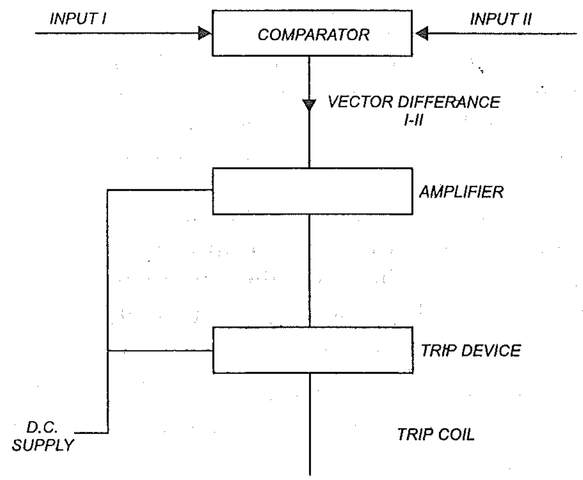


Fig. 41.1. Static differential relays principle.
(Simplified block diagram)

Rectifier bridge comparator can be used conveniently in static differential relay. Block diagram is such a relay is given in Fig. 41.1.

Merits of Static Differential Protection

(*Courtesy* : Brown Boveri, Switzerland)

— Three phase relay set with small dimensions.
— Absolute stability for heavy through faults, hence ideally preferred for large transformers, generators.
— High sensitivity for internal faults.
— Extremely short tripping times regardless of magnitude of auxiliary voltage (*e.g.* 20-50 ms).
— Accurate and absolutely stable tripping characteristic even for asymmetrical faults as each phase can have its own relay.
— Inrush-proof, even during high-starting currents, inrush currents.

— Low consumption (VA burden on CT's , VT's)
— Easy selection of auxiliary voltage.

Applications

— Protection of generators.
— Protection of generators-transformer units.
— Protection of two winding transformers.
— Protection of three winding transformers.

For

— Two and three phase faults.
— Earth faults in transformers with solidly grounded neutral or low resistance grounded neutral.
— Earth faults in generators with solidly grounded neutral or low resistance grounded neutral.
— Inter-turn faults.

41.2. DIFFERENTIAL PROTECTION OF TWO-WINDING TRANSFORMER

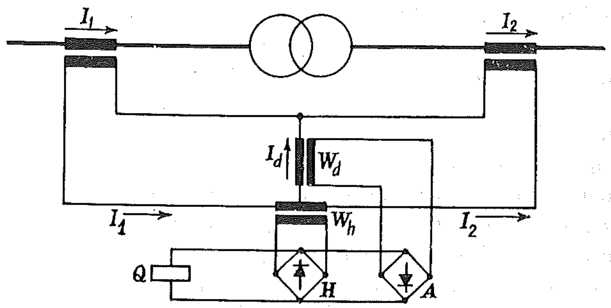
(Please Ref. Sec. 28.3, 32.5, 33.3)

Refer Fig. 41.2, which illustrates static differential protection of a two winding power transformer.

The differential relay is connected to the current transformers on either sides of the object (generator/transformer) to be protected. The incoming and outgoing currents are compared by the *differential circuit.*

When there is an internal fault in the protected zone, the differential current (I_d) increases. When the differential current (I_d) exceeds the picking level (usually 0.5 I_N) the relay operates.

The pick-up value depends on ratio of differential current (I_d) and through current $\left(\frac{I_1+I_2}{2}\right)$. The relay is thus biased or compensated to take care of through fault currents.



I_d = Operating (differential current)
$\left(\frac{I_1+I_2}{2}\right)$ = Restraining current
Q = Tripping Relay
W_d = Auxiliary CT for operating current I_d
W_h = Auxiliary CT for restraining current $(I_1+I_2)/2$.
A = Rectifier for forward (operating) current
H = Rectifier for restraining current.

Fig. 4.2. Differential protection of two winding transformer by static differential relay.

In static differential relay circuit, an auxiliary CT (W_d) is connected in operating current (I_d) circuit and another auxiliary CT (W_h) is connected in restraining (bias) circuit. (Ref. Fig. 41.2) The secondaries of these auxiliary CT's are connected to rectifier bridge comparator (Ref. Ch. 39)

The output of operating auxiliary CT W_d is given to rectifier bridge A, whose output gives forward current to the tripping device Q.

The output of restraining auxiliary CT is given to rectifier bridge H, whose output gives restraining current to the tripping device Q. The tripping device receives the forward current which is a difference of I_A and I_H.

$$I_o = I_A - I_H$$

where I_o = Operating current in forward direction in tripping device.
I_A = Output of rectifier A in the forward direction.
I_H = Output of rectifier B in reverse directional.

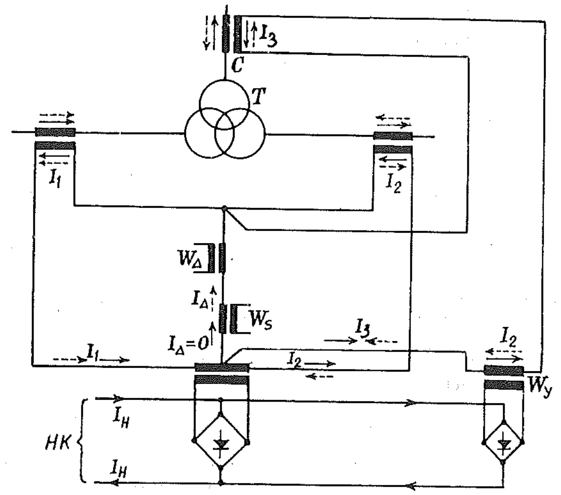
when I_o exceeds the pick-up value, the relay operates.

The tripping relay is generally permanent magnet moving coil relay.

41.3. DIFFERENTIAL PROTECTION OF THREE WINDING TRANSFORMER

The principle of the differential protection of three winding transformer is the same as described for two-winding transformers.

To protect three-winding transformer additional components are needed. A reliable differential measurement is only guaranteed under all possible operating conditions when a separate restraint circuit is also provided for the third winding. The circuitry is illustrated in Fig. 41.3, and Fig. 41.4.

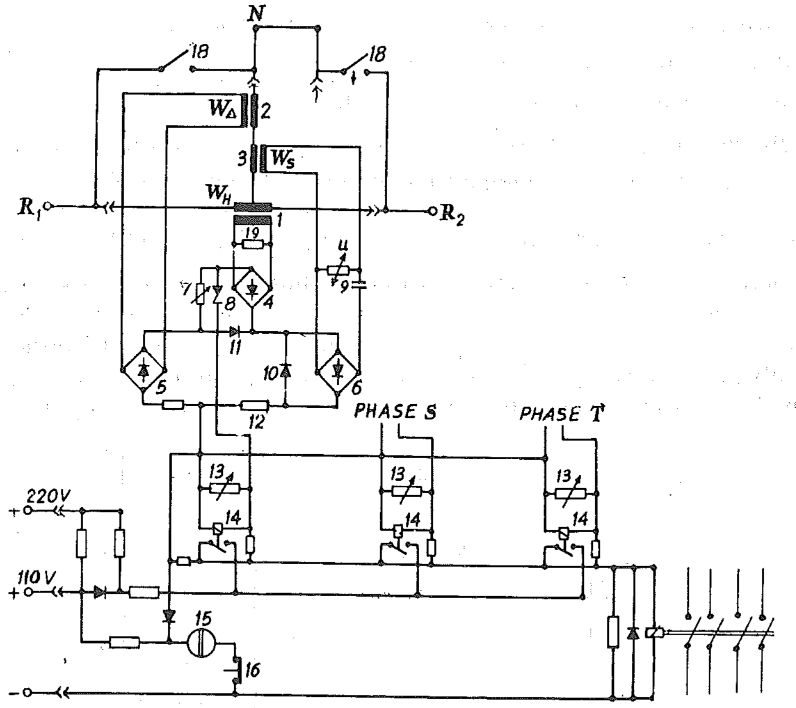


T	Transformer protected
W_H	Restraining current transformer (Ref. Fig. 41.2)
W_R	Additional restraining current transformer
W_S	Blocking transformer for stabilisation circuit
W_*	Differential current transformer
$\rightarrow I_1, I_2, I_3$	Currents during normal service.
$\rightarrow I_1, I_2, I_3$	Currents during fault inside the protected zone.
I_Δ	Differential current
I_H	Restraining current
HK	Restraining circuit.

Fig. 41.3. Principle of measurement of differential protection for a three winding transformer.

By connecting the two restraint circuits W_H and W_Y in parallel on the d.c. side, restraint is assured in the event of a through fault, even if it flows through the third transformer winding into the part of the system connected to it.

The restraining action of two circuits W_H and W_Y is equally strong when the through currents are equal ($I_1 = I_2 = I_3$), as the circuits are so designed that $I_H = \frac{1}{2}(I_1 + I_2)$ through W_H produces the same restraining effect in the relay as $I_Y = I_3$ through W_Y. When the currents are different ($I_1 \neq I_2 \neq I_3$), restraint in the relay is governed by the highest value, *i.e.* either $I_H = \frac{1}{2}(I_1 + I_2)$ or $I_Y = I_3$, depending on which is larger. The smaller is not taken into accounts.



1. Restraining current transformer W_H
2. Tripping current transformer W_H
3. Blocking transformer W_H (Air gap transformer)
4. Restraining current rectifier bridge.
5. Difference current rectifier bridge.
6. Blocking current rectifier bridge.
7. Resistance for bias setting.
8. 'Zener' diode
9. Non-linear resistance
10. Blocking current limiting diodes.
11. Diodes
12. Plug-in blocking element
13. Resistance for basic setting
14. Moving coil-relay
15. Annunciator
16. Reset button
17. Tripping contractor
18. Automatic shorting links
19. Restraining circuit resistance

R_1, R_2 Input terminals of the phase R
N Neutral of current transformer sets.

Fig. 41.4. Circuit diagram of three-phase differential relay in Fig. 41.3
(*Courtesy* : Brown Boveri, Switzerland)

The circuit diagram of the R phase of three phase differential relay is illustrated in Fig. 41.4. The auxiliary tripping c.t. $W\ \Delta$, restraining *c.t.* W_H and blocking transformer W_s correspond to those shown in Fig. 41.3.

41.4. INRUSH-PROOF QUALITIES.

When a transformer is switched on, a current surge is produced which eventually reverts to the charging current of the transformer. It only occurs on the closed side and is therefore experienced by the relay as a difference current. Difference currents of similar shape but shorter duration can also be produced in the differential protection of generators by current surges resulting from momentary differences in the behaviour of the current transformers.

The oscillogram in Fig. 41.5 shows the inrush current with severely distorted waveforms produced when a transformer is switched on. Analysis of this curve indicates the presence of a large amount of the second harmonic. To make the relay inrush proof this 2nd harmonic component of the difference current is employed, in that this current, after resonance amplification is fed to the moving-coil relay in the blocking direction. The resonance amplification is performed by a filter in

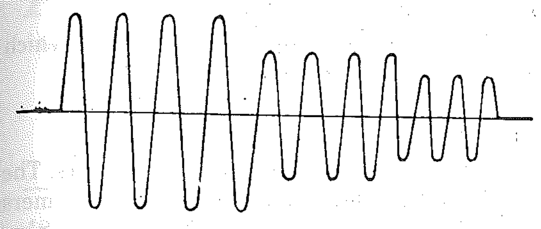


Fig. 41.5. Oscillogram on inrush current of transformer.

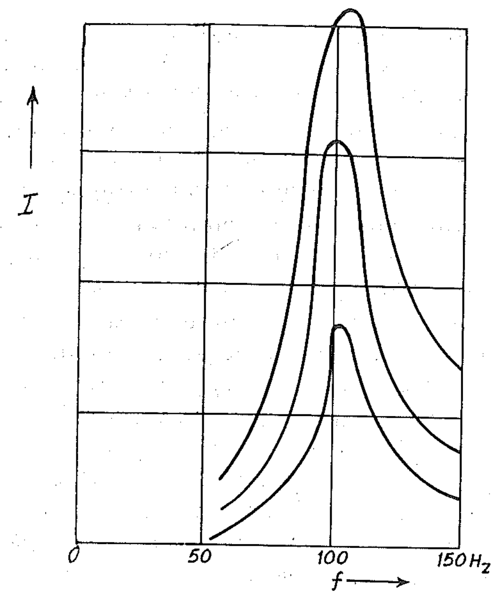


Fig. 41.6. Frequency characteristic of harmonic filter for three magnitudes of inrush current.

the secondary circuit of the blocking transformer W_s. (Ref. Fig. 41.3). The frequency characteristics of the filter are shown in Fig. 41.6 for three different currents.

Since this blocking action is only sensitive to the second harmonic which of course is characteristics for inrush surge of power transformers the relay is certain to distinguish between an inrush and a short circuit in the protected object.

Ref. Fig. 41.4. The blocking current is diverted through diode 11 so that it does not have to flow through the resistor 7 used for setting the bias or the rectifier bridge 4 for the restraining current. By this means the blocking properties are quite independent of the bias.

41.5. REQUIREMENTS TO BE FULFILLED BY THE MAIN CT

Although the relay, on account of the restraining action described is fairly insensitive to C.T. saturation, the main C.T. used should not reach the saturation point at the connected burden and at the maximum fault current experienced. It has proved advantageous in practice to allow for an overcurrent factor of at least 10. The corresponding C.T. class is 5P10, *i.e.* between 0.33 and 10 I_N the current error is less than 5% and the angular error less than 300. The C.T. load in this case consists of all connected loads, such as the leads, auxiliary C.T., the differential relay and any other elements connected, the consumption being referred to the rated current of the C.T. If the C.T. is loaded below its rated burden, the overcurrent factor rises in the ratio of the actual load plus C.T. consumption to the rated output plus C.T. consumption.

On account of the very short tripping time of the relay, allowance has to be made for dynamic phenomena in the transformation of the short circuit. It is therefore advisable to make the secondary time constants of the circuits on either side of the relay nearly equal as possible, *e.g.*, by using auxiliary transformers on either side of the relay. In the case of three-winding transformers or unit-connected generators and transformer with feeders to the units auxiliaries, C.T. ratios which relate to very different powers should be avoided. In other words, the ratios of the differential protection cores of all main C.T. should be based on the same power *i.e.* the highest.

41.6. AUXILIARY C.T.

These C.T. have to perform various duties, including :

1. Restoration of the phase shift between the currents on the primary and secondary sides of a power transformer, caused by the connection of the windings.

2. Ensuring that when the same power is being carried by the two transformer windings, the same flows to the relay from both sides and that, at the full power of the winding, the current flowing to the relay is at least 0.7 times the relay current.

3. Filtration of zero-sequence currents when the transformer neutral is earthed, or in auto-transformers. For this purpose the auxiliary C.T. shall be connected in star/delta on that side of the transformer which has its neutral earthed.

4. Auxiliary C.T. should never be employed on only one side. With an asymmetrical arrangement the different transient response of the two circuits in the event of through short circuits can give rise to considerable difference currents which could cause the extremely rapid relay to operate.

In order to keep the burden on the auxiliary C.T. as small as possible, they should be mounted as close to the relay as can be permitted.

Apart from individually matched auxiliary c.t., it is also possible to supply universal c.t. which are suitable for use in the majority of cases.

Summary

Static differential relays are preferred for protection of large generators and transformers. The principle is similar to that of conventional differential protection. Additional auxiliary transformers are used in secondary circuit of main CT's. The output of operating auxiliary CT and restraining auxiliary CT is supplied to rectifier bridge comparator. A permanent magnet moving coil relay is used as tripping device.

QUESTIONS

1. Describe the circuit of static differential relay for protection of two winding transformer.
2. Describe the circuit of a static differential relay for three winding transformer.
3. Write short notes on any two :
   — use of rectifier comparator in static differential protection of two winding transformers
   — advantages of static differential protection
   — inrush proofing in static differential protection of power transformers.
4. Describe the difficulties in conventional differential protection of power transformers. State the merits of static protection. Explain clearly the additional features in static protection schemes.
5. Describe the rectifier bridge comparator used in static differential protection of power transformer. Illustrate the provision of blocking during inrush currents.
6. Explain the requirements of main and auxiliary CT's (intermediate CT's) in static differential relays.

42

Static Distance Relays and Distance Protection of EHV Lines

42.1. INTRODUCTION

The principles of distance protection are discussed in Ch. 29 and distance protection of transmission lines is described in section 30-*B*. The principles of carrier aided distance protection have been briefly mentioned in sec. 30.14.

This chapter deals with *advanced topics in distance protection of HV and EHV lines with particular reference* to static distance relays.

The principle of measurement of impedance (distance) is the same in both electromagnetic relays and static relays (Ref. Sec. 29). However static distance relays offer several advantages.

Merits of Static Distance Relays.

— no moving parts in measuring circuit, hence no effect of vibrations, shocks, dust.
— faster operation 20 ms, 40 ms, 60 ms
— less burden *e.g.*, burden of CT : 0.9 VA to 4.2 VA during normal and short circuit conditions respectively. Burden on VT : 2.2 to 12 VA during normal and short-curcuit condition respectively. This results in more economical CT's, VT's and better accuracy.
— comparator with elliptical or quadrangular impedance characteristics on R -X plane can be used. Such characteristics are *not* possible by electromagnetic distance relays whose characteristics are limited to sectors of circles on R-X plane.
— greater adoptability due to large range of adjustments and characteristics.
— Versatile range of relays available for various specific applications.
— better stability under power swing conditions.
— suitable for long heavily loaded lines, cables, even distribution lines.
— cover all types of faults selectively, *e.g.*, single line to ground, line to line, three phase.
— can have distance time step characteristic with four *independently* adjustable time steps and impedance zones.
— lower impedance setting possible
— fast tripping of first step — selector switches for
  — under reach and over-reach
  — rapid auto-reclosure or delayed reclosure
  — programmed auto-reclosure
— provision of contacts for remote annunciation of kind of fault, step of operation, tripping
— possibility of temporary reversal of measurement direction of second or second and thrid zones.

— compact size (450 × 750 × 200 mm) of a three phase, four step relay and less weight (50 kg) compared with several electromagnetic relays accommodated on a complete separate panel to perform similar functions.

— No wonder, static distance relays with their several merits are rapidly replacing their electromagnetic competitors. There are two distinct applications of these relays.

— medium high voltage (12 kV, 36 kV, 72.5 kV) distribution lines where multistage distance relays are now replacing usual overcurrent time delay relays. By distance schemes it is possible to have greater selectivity, shorter interruption times.

— EHV transmission line (145kV, 245kV, 420 kV) in conjunction with carrier signals. The main advantage of carrier aided distance protection schemes is that only tripping or blocking command is transmitted over transmission line. Transmission of pure command (not derived from main current) in digital values, provides greater security in transmission to the condition.

Section 1. COMPARATOR COMBINATIONS IN DISTANCE RELAYS

42.2. VOLTAGE COMPARATOR AND CURRENT COMPARATOR

As described earlier, the distance relay compares the ratio $\frac{V}{I}$. It is set to an impedance $\frac{V}{I} = Z$, such that for a fault at a certain distance from relay location the relay operates if the impedance of the line, upto the fault point is less than the above relay setting Z.

The versatile family of distance relays includes impedance relay, Reactance relay, Mho relay discussed earlier. The measurement of impedance, reactance or admittance is done by comparison of input combinations of current and voltage. Hence distance relays have input current and voltage. In static comparators the two quantities to be compared must be similar, *e.g.* current/current or voltage/voltage.

Voltage Comparator

Current I is converted into equivalent voltage V_A by producing a voltage drop in an impedance Z. The voltage drop is then compared with other voltage (Fig. 42.1).

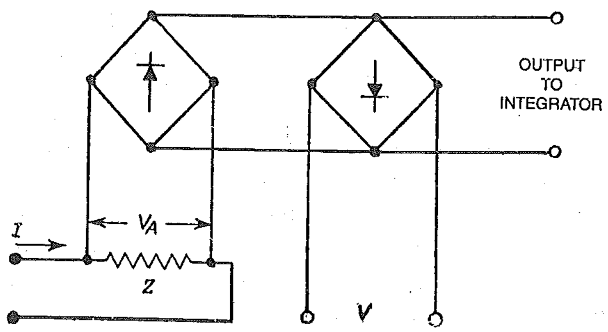


Fig. 42.1. Distance relay based on voltage comparison principle.

Block Diagram of a Static Distance Relay

A block diagram of a static distance relay is given in Fig. 42.2. The line *PT* secondary is connected to auxiliary *PT*. The output of VT is converted into current. This is compared with the output of VT.

Let us come back to Fig. 42.1. In voltage comparator, the current is converted into voltage by passing it through impedance $Z < \theta$ which is a replica of the protected line section on a secondary basis. It means the IZ drop given to the rectifier bridge is compared with to line voltage V.

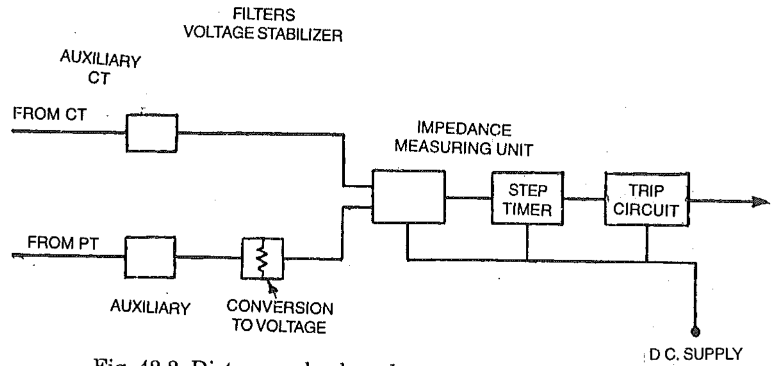


Fig. 42.2. Distance relay based on current comparison principle.
[*Courtesy* : Brown Boveri, Switzerland.]

Current Comparator

Alternatively in current comparator, a current is derived from CT and the voltage from VT is converted into equivalent current V/Z by connecting a replica impedance (impedance which is a small scale version of line impedance) in series in VT secondary (Fig. 42.3).

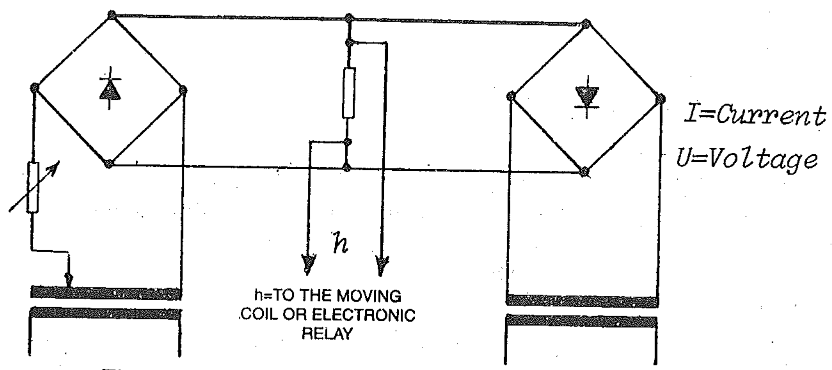


Fig. 42.3. Distance relay based on current comparison principle.
[*Courtesy* : Brown Boveri, Switzerland.]

The current is secondary of VT corresponds to V/Z which is compared with I.

The use of replica (image) impedance permits faster tripping as it eliminates errors due to transients in fault current. This needs explanation. The transient d.c. component of current passing through line impedance produces a faithful voltage waveform which is derived from line VT. The secondary current of line VT (V/Z) has faithful transient. The comparator compares V/Z and I, both having identical transient (assuming faithful reproduction). Hence the effect of transient is cancelled out from Impedance Measurement.

The use of replica impedance reduces the influence of harmonic and transient d.c. components substantially.

The rectifier bridge current comparator (Fig. 42.4) receives two current inputs, say operating input I_O and restraining input I_R. The output of comparator is applied to a permanent magnet coil relay or a static level detector.

In distance relays, I_O *and* I_R *may be supplied either by the current transformer by a voltage transformer through a series impedance (Fig. 42.3) or by both sources in a particular combination to obtain particular relay characteristic.*

(*i*) **Impedance Relay**

If restraining current I_R is supplied by voltage transformer, and operating current I_O is supplied by current transformer (Ref. Fig. 42.4), the relay operates when the ratio V/I is less than a certain value Z_N and is therefore a minimum Impedance Relay.

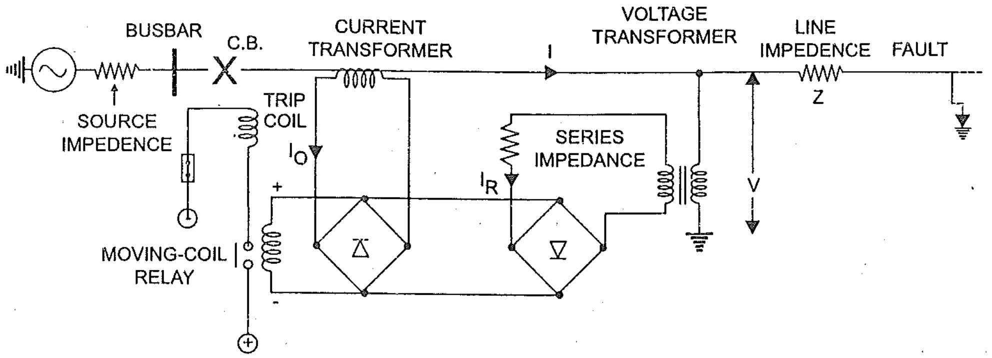


Fig. 42.4. Comparator used in an impedance relay.
[*Courtesy* : A Reyrolle and Co. Ltd., England.]

(*ii*) Directional Impedance Relay

If I_R is supplied by current transformer and also by voltage transformer ($I_R = K_1I - K_2V$) and I_O is supplied by current transformer and voltage transformer ($I_O = K_1I - K_2V$), the relay operates when

$$I_0 > I_R$$

i.e. $$K_1I + K_2V > K_1I - K_2V$$

With this characteristic, the relay operates for a particular phase relation between V and I, restrains for some other.

In other words the relay has *Directional Characteristic.*

Here directional characteristic has been obtained by a particular combination of inputs to the comparator. (Ref. Fig. 42.5) through auxiliary mixing transformer.

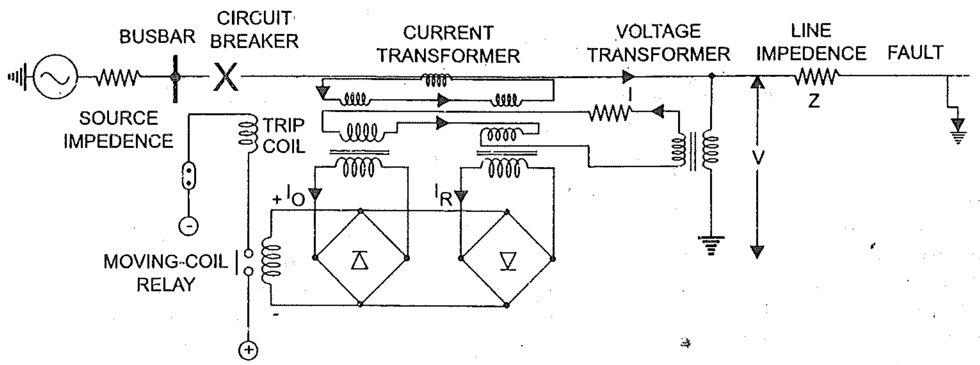


Fig. 42.5. Comparator used as a directional relay.

By use of auxiliary mixing transformer, combination of inputs, replica impedances, dummy impedances input to comparators, a variety of characteristics can be achieved. These are called Mho, off-set mho, elliptical quadrilateral characteristics.

(*iii*) Offset Mho Relay

Fig. 42.6 illustrates use of comparator as an off-set Mho Relay. The comparator receives inputs through mixing transformer. The circuit is designed such that the relay operates when V and I have phase angle within certain limits (Directional feature) and ratio V/I is less than a certain value Z_n. However, if direction of power flow is reversed, the phase angle between I and V changes and then the relay operates when ratio V and I is less than KZ_n, which is less than unity. The charac-

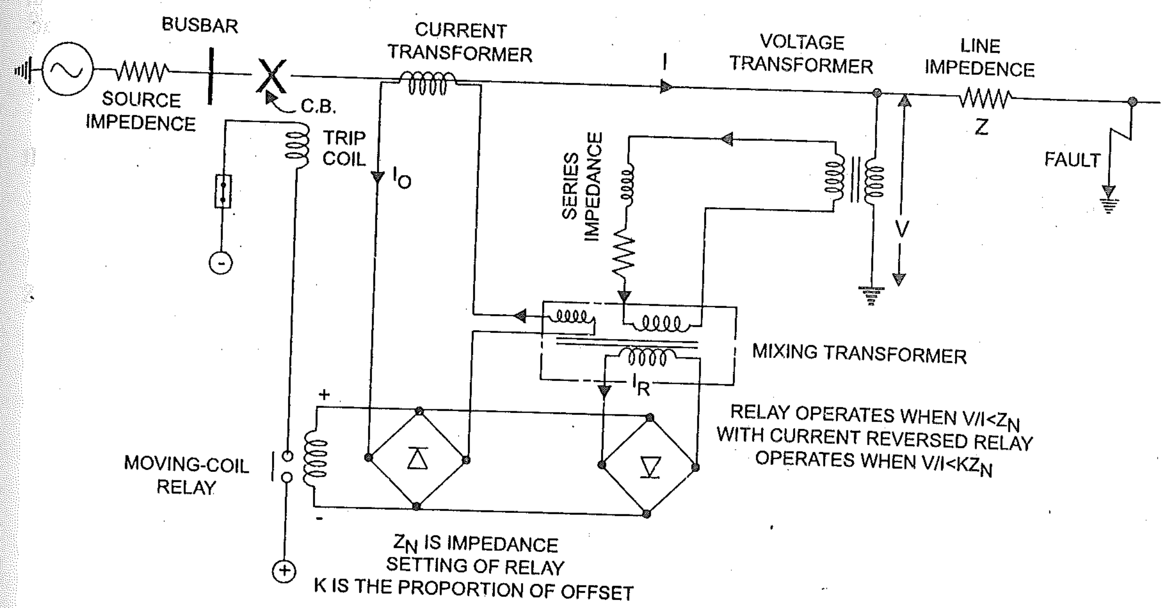


Fig. 42.6. Comparator used as an offset Mho relay.
[*Courtesy* : A Reyroll and Co., England.]

teristic if such a relay (Fig. 42.7) is called off-set Mho'. On R-X plane, it is a circle whose circumference encloses the origin and is slightly offset.

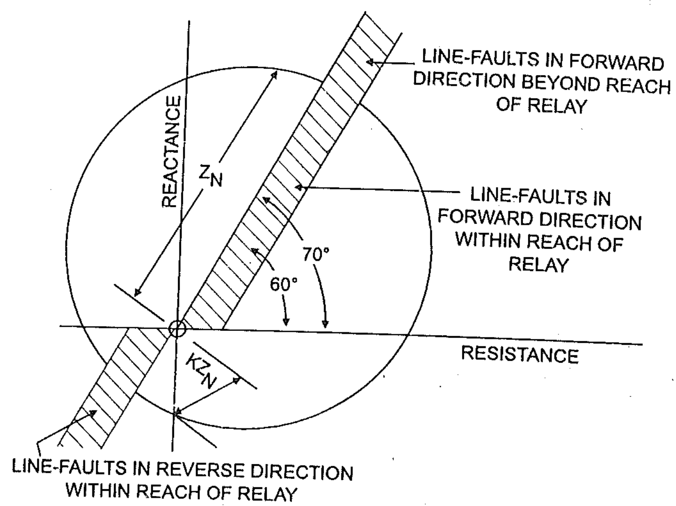


Fig. 42.7. Circle characteristic of offset mho relay.
Courtesy : A Reyroll & Co. Ltd., England.

Multi Input Comparators

The basic principles of amplitude and phase comparators were described in Ch. 39. In sec. 42.2, we studied comparators having two input.

Distance relays can be either single phase or polyphase and employ multi-input comparators. Such multi-input comparators are either integrating or instantaneous type and compare either amplitude or phase or both.

The characteristic of conventional double input comparators is in form of circles or sectors of circles on R-X plane. Multi-input comparators can have elliptical, conical or quadrilateral characteristic on R-X plane.

42.3. THREE-INPUT AMPLITUDE COMPARATOR

Fig. 42.8 illustrates a current comparator with three inputs. It is an amplitude comparator. It comprises three rectifier-bridges.

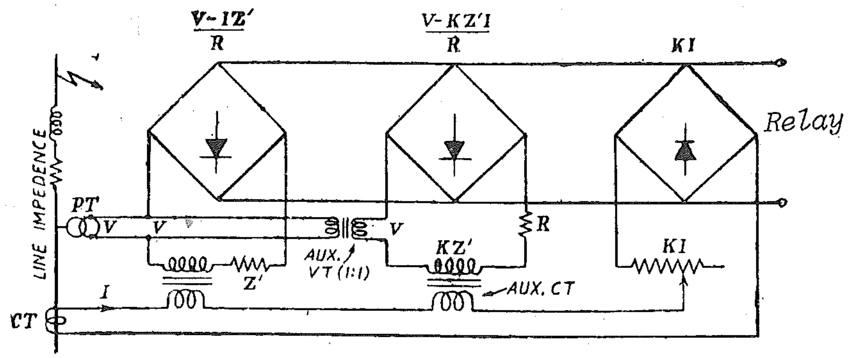


Fig. 42.8. Current amplitude comparator with three inputs giving characteristic Fig. 42.9.

The three bridges get the inputs derived from output VT, CT and mixing transformer. The voltage should be converted into current (Ref. Fig. 42.3). The ultimate characteristic of a particular bridge comparator will depend upon the combination of input circuits. In the circuit under-consideration, the three-inputs are

$$\frac{V - IZ'}{R}, \frac{V - KIZ'}{R} \text{ and } KI.$$

where Z and KZ are replica impedances of same phase angle as that of protected line. The amplitudes currents compared by the bridge are

$$\left|\frac{V - IZ'}{R}\right|, \left|\frac{V - KIZ'}{R}\right| \text{ and } |KI|,$$

the polarity of the bridge of KI being opposite of the other two.

In balance condition, the comparator output is zero.

$$\frac{V - IZ'}{R} + \frac{V - KIZ'}{R} = KI \qquad ...(42.1)$$

where **Z' is replica** impedance in the relay,

K is the constant to be selected.

Dividing by I, and multiplying by R.

$$\frac{V}{I} - Z' + \frac{V}{I} = KZ' = KR \qquad ...(42.2)$$

But V/I is the impedance of line section measured by the distance relay call it Z

$$(Z - Z') + (Z - KZ') = KR$$

In impedance diagram on $R - X$ plane, Z is the line impedance V/I measured by relay plotted as a characteristic. Whereas Z' is constant replica impedance used in the relay and K and R are **constants** for a particular setting

$Z - Z'$ is 0, as seen later in Eqn. 42.6

rewriting Eqn. 42.3, we get

$$(Z - Z') + (Z - KZ') = KR = 0$$

This is a general equation of the three-input distance relay shown in Fig. 42.8.

The locus of the arrow head of vector Z measured by relay traces a curve on R-X plane by obeying Eq. (42.4).

Obviously the locus will depend on selected values of K, R and Z'.

Suppose, $$K = \left|\frac{Z' - KZ'}{R}\right| \qquad ...(42.5)$$

Substituting in Eqn. (42.4) reduces to

$$| Z - Z' | + | Z - KZ' | - | Z' - KZ' | = 0 \qquad ...(42.6)$$

$$Z - Z' = 0.$$

Which is a plain impedance characteristic, with a circle having centre at origin and radius as Z'

Suppose $k < \dfrac{| z' = kz' |}{R}$,

Substituting in Eq. (42.4)

$$| Z - Z' | + | Z - kZ' | < | Z' - kZ' | \qquad ...(42.7)$$

The impedance characteristic of Eq. (42.7) is illustrated in Fig. 42.9.

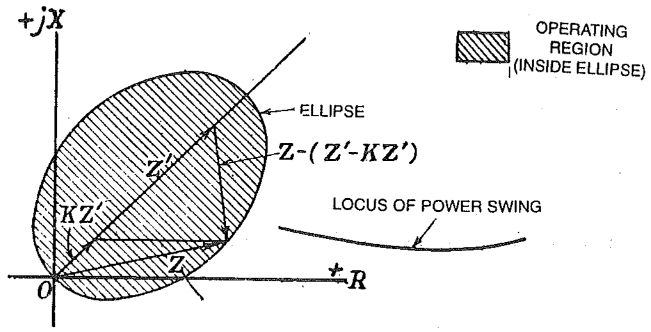


Fig. 42.9. Characteristic of three-input comparator with equation 42.7.

It is an ellipse passing through origin of R-X diagram. The first two terms are distance of foci from the curve and the term on right side is the major diameter.

We will recall that when V/I measured by relay is beyond the characteristic, the relay does not operate. During power swings, the elliptical characteristic with narrow coverage across R axis is less liable for tripping than circular into characteristic.

42.4. HYBRID COMPARATOR

The hybrid comparator compares amplitude and phase. It is a combination of amplitude comparator and phase comparator.

The hybrid comparators are generally multi-input comparators. The three (or more) inputs are derived from output of CT and VT by means of replica impedances, mixing transformers, auxiliary CT's and VT's (Ref. Fig. 42.8 for example)

Two of the inputs are supplied to an amplitude comparator. The output is compared with third input in a phase comparator. Alternatively, two inputs are phase compared and output is amplitude compared with third input.

Refer Fig. 42.10. The phase comparator receives sinusoidal input V and squared input IZ'. The amplitude comparator receives three inputs V, IZ and output of phase comparator $[(V, I, \angle\phi)]$.

The characteristic of Hybrid comparator depends upon the three inputs.

The Fig. 42.10 describes instantaneous relay. There is no integrator in the block diagram.

Example for Practice : Develop a block diagram of a integrating hybrid comparator V and I input. Describe the functioning of the relay.

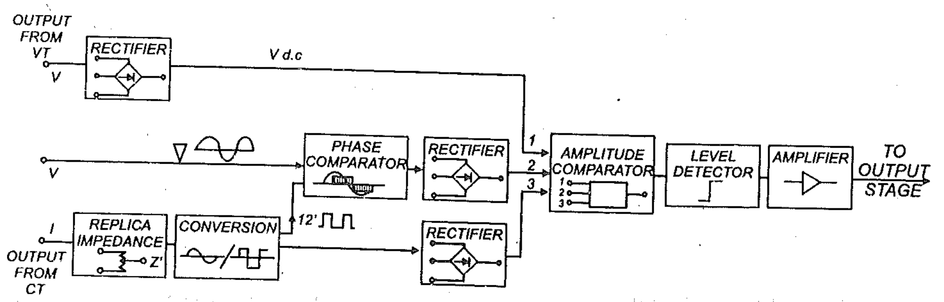


Fig. 42.10. Block diagram of a hybrid comparator used in a Static Distance Relay (Instantaneous Type)

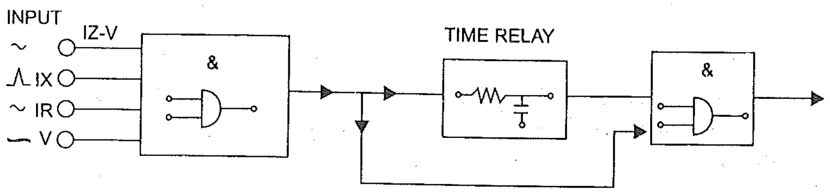
42.5. FOUR INPUT PHASE COMPARATOR WITH QUADRANGULAR CHARACTERISTIC

Ideally, the characteristic of distance relay should overlap the fault area [Fig. 42.11(*c*)]. In circular characteristic, offered by conventional distance relays, extra area is unnecessarily covered. This makes the relay vulnerable to operate under power swings. With static relays with four-input comparators. It is possible to achieve quadrangular (quadrilateral) characteristic [Fig. 42.11 (*b*)]. The four-inputs required for quadrangular characteristics are say,

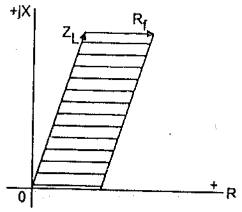
$IZ - V$ .... (Sinusoidal)
IX .... (Pulse)
IR .... (Sinusoidal)
V .... (Sinusoidal)

These are given to AND gate

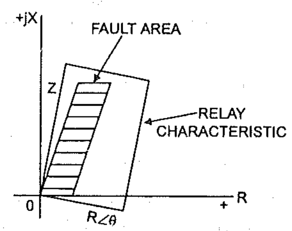
The interaction between IX and V is eliminated by converting one of them into pulses. The delay unit ensures that comparison of all into satisfy the AND condition for the period decided by the delay unit.



(*b*-1) Block-Diagram.



(*a*) Z_L = Line Impedance
R_F = Fault Resistance
Fault Area on R-X plane



(*b*-2) Quadrangular Characteristic
(*b*) Four-input phase comparator

Fig. 42.11.

42.6. ERRORS IN DISTANCE MEASUREMENT

Distance measurement is affected adversely by the following :

— fault resistance (Ref. Sec. 29.3)
— power swings, hunting
— double circuit lines
— bilateral infeed in the protected line
— series capacitors for compensation
— T'eed lines

These problems and their solutions will be discussed in this section.

Distance Measurement : **Impedance as seen by the Distance Relay.**

42.7. INFLUENCE OF POWER SWINGS ON DISTANCE PROTECTION

42.7.1. Power Swings, What are they ?

As we know, a sudden change in the load of a synchronous generator or motor cause oscillations of the power angle about its new equilibrium position, a similar phenomenon occurs in the power transmission through line interconnecting two sources when subjected to a sudden change in the load transfer.

The power transferred through an interconnecting line is given by

$$P \propto \frac{E_1 \cdot E_2 \sin \delta}{X}$$

where P power transfer in watts
E_1, E_2 internal voltages of synchronous machines at sending end and receiving end
δ phase angle between E_1, E_2.

Ref. sec. 44.2 ; the sudden change in loading causes a sudden change in angle δ. Then vectors E_1, E_2 the oscillate between their new equilibrium positions. Thereby, the current vectors at sending end and receiving end also oscillate between their new equilibrium positions. Thus the oscillations are set-up in the voltage and current at sending end and receiving end.

The power transferred through the transmission line is given by

$$P = V_{12} I_{12} \cos \theta$$

V_{12} vector difference between sending end voltage and receiving end voltage.
I_{12} current transferred through the line
θ phase angle between V_{12}, I_{12}
P will be positive at sending end and negative at receiving end.

As the load suddenly changes, vectors E_1, E_2 and vectors V_1, V_2 oscillate, vector V_{12} and I_{12} also oscillate about their respective final equilibrium positions.

This produces power swings which lead to flow of heavy equalizing currents I_{12} between the two ends. Such power swings are more severe when a sudden short-circuit occurs in the sending end station/receiving end station or in transmission line and the circuit-breakers are opened and reclosed. Power swings can occur by disconnection of a large load (one of the outgoing lines or generators).

During power swings, the measurement of V/I performed by distance relays at sending end and receiving end is affected. The distance relay may operate even when there is no fault.

This disturbance at the station busbars affects the neighbouring system and a large zone of the system is subjected to power swings. In Interconnected system where a large proportion of primary protection is by distance relays, this may lead to *indiscriminate tripping at various points in the system,* resulting in cascade tripping and a total black-out. Hence the performance of distance relays and remedial measures under power swing conditions need careful attention.

42.7.2. Effect of Power Swing on the Starting Elements in Distance Schemes.

(Ref. Sec. 30.10, 30.11, 30.13)

The starting elements in distance schemes (Ref. Sec. 30.10) usually respond to either overcurrent or under-impedance.

Overcurrent relays respond to increased current. During power swing conditions, there is a heavy flow of equalizing currents in the transmission lines. Since the phenomenon of power swings is symmetrical, the equalizing currents flow equally in all three phased and cause over-current starting relays of all three phases to pick-up.

The minimum impedance starting relays (Ref. Sec. 30.10) measures V/I. When V/I drops below the setting Z', the starting relay operates. During power swing condition, voltage V drops a certain point of network, equalizing currents increase. Hence minimum impedance starting relays in all three phases operate and remain operates till the power condition persists.

42.7.3. Effect of Power Swing on the Measuring elements in Distance Schemes.

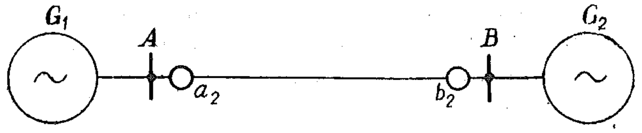
Ref. Sec. 30.10. The *starting element* also called *fault detector* acts first and switches *measuring element* to appropriate input quantity. During power swings, starting elements gets actuated and picked-up as described above and appropriate input quantities are now applied to the measuring elements.

The measuring element should distinguish whether the power swing condition is persisting or not. It should also distinguish whether reduced V/I is due to power swing or a real fault. Usually there is a provision 'blocking'. *Blocking* refers to making the protection scheme in-operative under certain conditions. The measuring elements get blocked during power swings within permissible limits and tripps during faults. In one of the blocking schemes, the measuring element has low output during power swing condition but higher output during fault condition. In another conventional blocking scheme, the blocking unit opens the trip circuit during power-swing conditions.

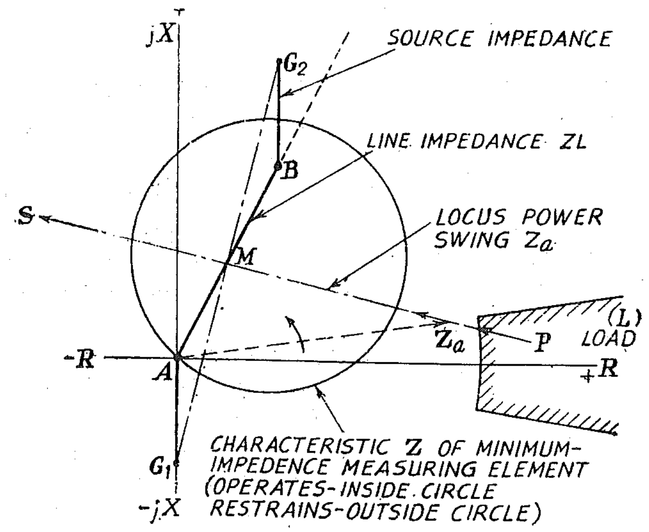
42.7.4. Representation of Power Swing on R-X diagram

Fig. 42.13 (b) represents the source and line impedance on R-X plane.

The conditions of a power swing can be represented on a impedance diagram, as shown in Fig. 42.12. For the simplified case of two generators G_1 and G_2 connected by a tie-line impedance Z_L,



(a) Two machine system with interconnector AB.



(b) Representation of source line impedance, apparent impedance on $R-X$ plane (Impedance Diagram)

P_S	Locus of power swing (apparent impedance Z_a		
G_1, G_2	Generating/Motoring sources in two machine system.		
a_2, b_2	Distance relays	A, B	Busbars near a_2, b_2
G_1A, G_2B	Source impedance'	AB	Line impedance
L	Load impedance	Z_a	Apparent impedance
Z	Characteristic of impedance relay, (Circle).		

Fig. 42.12. Explaining power swings.

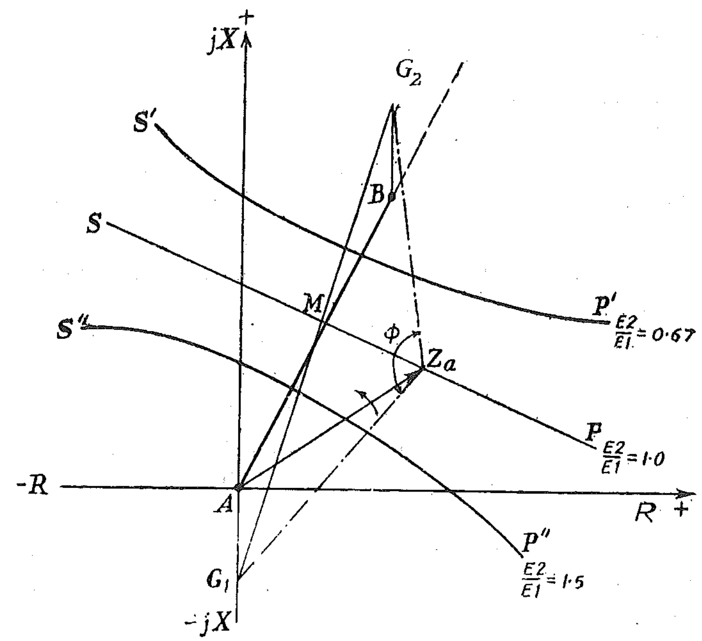


Fig. 42.13. Conditions of a power swing on an impedance diagram. (R-X Plane) (Ref. Fig. 42.18).

A	Relay point of near busbars A
AB	Line impedance ZL
A, B	Bus bars
G_1, G_2	Sources in two machine system
$PS, P'S', P''S''$	Locuses of power swing (apparent impedance Z_a)
G_1A, G_2B	Source impedance
M	Mid of line AB
Z_L	Line impedance
Z_T	Total impedance
Z_a	Impedance seen by relay at A.

the source reactances of the generators and the impedance of the line can be represented on this diagram by the lines G_1A, G_2B and AB. The point at which relaying is being considered is taken as A, the origin of the diagram. The total impedance Z_r between the generated voltages E_1 and E_2 is represented by line G_1G_2.

Ref. Fig. 42.13. AG_1 and AG_2 represent generator internal reactances on R-X diagram. Since generator is predominantly inductive, its resistance is neglected and line AG_1, BG_2 are parallel to X axis. Line AB represents impedance of the transmission line on RX plane. Line AG_1 and AG_2 is the total impedance affecting the power swing. The locus of apparent impedance measured by the measuring element during power swing condition is by line PS approximately perpendicular to line AG_1 and AG_2 (Ref. Figs. 42.12 and 42.13).

Before the power swing V/I measured by the relay is in area L, far away from the circle Z. During the power swing the apparent impedance seen by the measuring element Z_a varies along with the swing and its locus is along line PS.

When the vector Z_a comes inside the characteristic circle-Z, the measuring element operates and relay gets tripped [Fig. 42.12 (b)].

Now let us apply the above method of analysis to get the locus Z_a for various ratios of generated voltages.

Remedial Measures to Prevent Operation of Distance Relays under Moderate Power Swing conditions

Under power swing conditions, the point Z_a (apparent impedance seen by the relay at station A) moves from right to left along line PS though there is no fault.

The blocking relay (out-of step relay) operates as the point Z_a touches its circular characteristic. The blocking relay blocks the circuit of the measuring relay for moderate power swing (say angle ϕ between E_1, E_2 upto 260°). As a result, for moderate power swings the distance protection does not operate.

For excessive power swings (say angle ϕ between E_1, E_2 more than 260°). The system is surely going to fall out-of step. In such case the blocking relay unblocks the main measuring relay. If the impedance seen by the main relay is less than the reach impedance, the relay operates.

42.8. PROTECTION OF TEED LINES BY DISTANCE RELAYS

In recent networks, the intermediate switching stations (Ref. Fig. 1.1) are being replaced by Teed Lines (T-off or lines with intermediate current source). The Teed Line with intermediate current feed from the T-off presents a problem in distance measurement.

Refer Fig. 42.15. Consider impedance seen by distance relay a_1 near busbar A. The *true impedance* seen by relay a_1 is the impedance between A_1, F_1 *i.e.* $Z_A + Z_B$. In absence of intermediate line T_C, the relay a_1 with measure this impedance.

With intermediate current infeed I_2, the situation changes. The apparent impedance seen by relay a_1 becomes

$$Z_T = Z_A + Z_B + \frac{I_2}{I_1} Z_B.$$

This being more than true impedance $(Z_A + Z_B)$ the fault appears to be farther away from actual location because of the mutual impedance effect due to current I_2, given by the third term on right hand side.

When current I_2 flows in intermediate Teed Line, the relay at station A will *under-reach, i.e.* protect less length of line that desired. (Since distance relay operates when Z_T is less than the relay setting Z_A and the Teed Line increases Z_r).

Because of the intermediate current in feed through Teed Line the distance relay from A does not protect the original length of line, for condition without the intermediate infeed.

Suppose, the high speed distance relays at a_1 is set to protect 80% of line AB. Suppose fault F is at 80% length of line AB, the relay a_1 will clear it when I_2 is zero but will not clear it if I_2 is present.

Hence the setting of relay at station A should be done by considering effect of intermediate infeed I_2. *It is practice to adjust the distance relays to operate as desired on the basis of no intermediate current infeed.* The fault F at the boundary of the first zone (say 80% of, AB) will not be seen by the first zone of relay a_1 but will be within the second zone of relay a_1. Second zone of relay a_1 covers complete AB plus part of line beyond AB but takes more time corresponding to the second step (Ref. Sec. 30.12)

42.9. BACK-UP PROTECTION WITH INTERMEDIATE INFEED

Consider back-up protection in distance protection scheme. This was described in Sec. 30.12 and Fig. 30.12. Now refer Fig. 42.15.

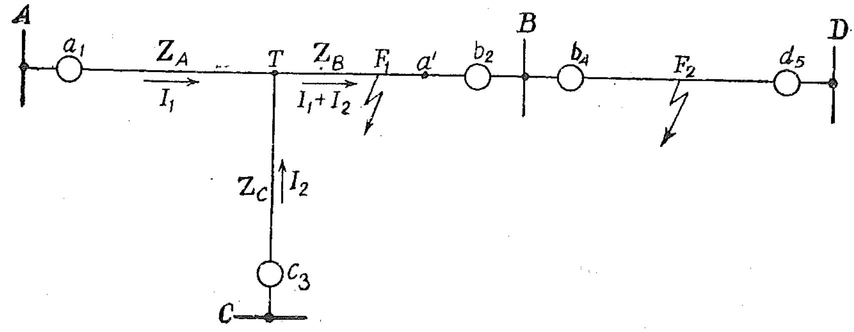


Fig. 42.15. Explaining effect of intermediate current source on distance measurement.

A, B, C, D	Busbars in different station
a_1, b_2, c_3, d_s	Distance Relays near A, B, C, D respectively
F_1, F_2	Faults
Z_A	Impedance between A, T
Z_B	Impedance between T, F
Z_C	Impedance between C, T
T	Point of Tee-off.

For a fault F_2 between B, D ; b_4 gives primary protection and relay a_1 gives back up. If breaker of b_4 fails to clear, breaker of a_1 should clear as a back-up. With intermediate infeed from C, the setting of relay a_1 for relay b_4 is a problem similar to that discussed in Sec. 42.10.

The fault F_2 should be *normally* in the second or third step of relay a_1 and first step of relay b_4. However, with the intermediate infeed from C, the fault F_2 is seen by relay b_4 as farther away and also by relay a_1 as farther away towards or beyond D. In extreme cases the apparent impedance seen by relay a_1 for fault F_2 may be beyond its third step and relay a_1 may not be sense the fault F_2 (Refer Fig. 30.12). Hence back-up protection by distance protection needs readjustment for lines with intermediate infeeds.

One solution to this problem is 'reversed third zone' by mho type distance relay with directional comparison type carrier current pilot relaying (Refer Sec. 30.14.2).

42.10. COMPENSATION OR COMPOUNDING IN DISTANCE RELAYS

Refer Sec. 30.10. Distance scheme has several measuring elements and starting elements. The response of the starting elements must be as fast as that of measuring elements so the speed of measuring elements is fully exploited. The minimum impedance relays (relays which operates for value of Z below its setting) operate when V/I measured by the relay is less than its setting.

The voltage V seen by the relay from the secondary side of VT is influenced by several aspects such as

— type of fault, *e.g.*. *L-G, L-L, 2L-G*.
— location of fault, whether near the measuring point or far away.
— VT connection with the relay.

The minimum impedance relays operate for reduced value of V and increased value of I. In EHV systems, particularly for single line to ground fault at the end of the line, these conditions are often not satisfied. In such case the relay does not operate and compensation or compounding is necessary compensation can be voltage compensation or current compensated.

"Compensation refers to feeding an additional input quantity in addition to main input quantity for the purpose of correction in performance characteristic. The additional input quantity supplements the main input quantity and provides compensation for measurement errors.

Consider voltage compensation (Ref. Fig. 42.8). The voltage comparator is supplied with phase voltage at its location and also phase voltage of the same phase compounded to about 70% of the line length. This compensation may be in the form of an replica impedance in voltage circuit of comparator to prevent input being effective until the desired value is reached.

For example the relay may operate with vector products of the two voltages (main and compensation) is less than the set value. When fault occurs at the remote end of line, the drop in only main voltage may not cause operation but the combined drop of main and compensating voltages may be enough.

Compensation may also obtained by introducing compensating current to the comparator of relay (Ref. Fig. 42.5). With current compensation, the relay may operate for lesser voltage (V/I remaining same). However, this compensation may not be preferred as it has to operate for very low voltages where accuracy is affected by other stray disturbances.

Section III. EXAMPLES ON SETTING OF DISTANCE RELAYS

42.11. SETTING OF DISTANCE RELAYS

We will now study the setting of impedance relay and mho relay for given line parameters. The *R-X* diagram is a powerful tool for analysis. The line characteristic and relay characteristic are drawn on the same *R-X* diagram.

We will recall that the line impedance is on the primary side of CT and VT, whereas the distance relay is on secondary side. To superimpose the line characteristic on relay characteristic both should be referred to the same side, preferably the secondary side. The following are the guidelines :

1. System quantities V and I should refer to the same phase corresponding the relay of that phase, *e.g.*, for earth fault protection of phase R, the voltage and current of phase R will be sensed by relay.
2. Voltage and current should be considered from the location of VT and CT.
3. Co-ordinates of *R-X* diagram must be in the same units (ohms).
4. Per unit system is preferred for large systems. Direct ohmic method may be used in simple problems.
5. Phase angles are important.
6. Both line characteristic and relay characteristic is referred to secondary sides and plotted on the same *R-X* diagram.

Conversion from Primary to Secondary Side

Line impedance on primary side is seen by the relay through CT and VT. The actual ohms of primary side should be converted to secondary side as seen by distance relay. This conversion is by means of a simple expression given below.

$$\boxed{Z_s = Z_p \times \frac{\text{CT ratio}}{\text{VT ratio}}}$$

where Z_s = Impedance as referred to secondary side of CT and VT and as seen by relay, ohms.

Z_p = Line/system impedance in ohms.

The same expression applies to R and X.

42.12. SOLVED EXAMPLES ON DISTANCE RELAY SETTING

Example 42.1. *Given. Line Impedance*

$Z_L = 2.5 + j5.0$

CT Ratio = *400/1*

VT Ratio = *33,000/110*

(*a*) *Plot line characteristic on R-X* plane referred to secondary side.

(*b*) *Plot characteristic of minimum impedance relay to protect 80% of the line length on same R-X* plane neglecting arc resistance.

(*c*) *Plot characteristic or mho relay having 45° maximum torque angle, to protect 80% of the line length, indicate the regions of operation and non-operation on the R – x diagram.*

Solution

(*a*) **Plain Impedance Relay** (Refer Fig. 42.16)

Line Impedance (given)

$$= 2.5 + j5 \text{ (Primary)}$$

i.e. $$Z_{L\ Primary} = 5.6 \angle 63.5° \text{ (Primary)}$$

Line impedance seen by relay through CT and VT is given by the equation.

$$Z_{L\ secondary} = Z_{1\ primary} \times \frac{\text{CT ratio}}{\text{VT ratio}}$$

$$= 5.6 \times \frac{400 \times 110}{33{,}000} = 7.47\ \Omega \text{ Secondary}$$

Draw on *X-R* plane line *AB* equal to 7.47 ohms at an angle $\theta = 63.5°$ with reference.

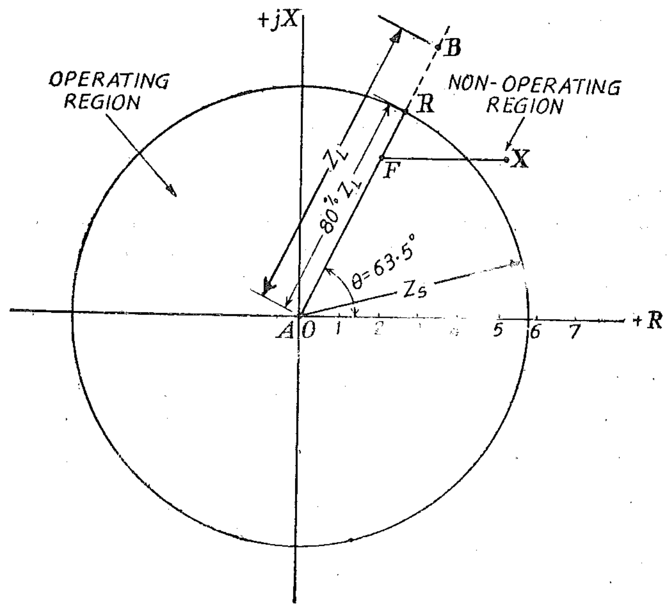
The setting of distance relay is such that it protects 80% of the line. Mark point R on line AB such that

AR should be reach of plain impedance relay. Hence setting of plain impedance relay Z_s is given by

$$A_s = AB \times \frac{80}{100} = 7.47 \times \frac{80}{100} = 5.98, \text{ ohms.}$$

Characteristic of impedance relay is a circle with origin O at A, radius AR = 5.98 ohms.

The relay operates for fault on transmission line between $A - R$ which lie within the circle.



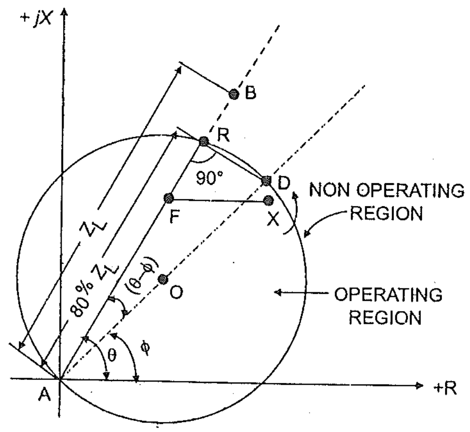
Z_L = 7.47 ohms (secondary)
Z_S = 5.98 ohms (secondary)
Z_F = 2.43 ohms (secondary)

AB line impedance Z_L seen from A
AR impedance of 60% length from A
θ angle of line impedance
O origin of impedance circle coincides with A
AF line impedance of 80% length from A, (Ex. 42.2)

Fig. 42.16. (Example 42.1 *a*) Line characteristic and plain impedance relay setting on *R-X* plane.

(*b*) **Mho-relay** (Refer Fig. 42.17)

Draw line *AB* and point *R* as in case *a*. The mho characteristic is different from impedance characteristic. mho characteristic is a circle passing through the centre of *R-X* plane and with axis along line of maximum torque.



Note : $(\theta - \phi) = \frac{AR}{AD}$

FX	Fault resistance (secondary)	*AB*	line impedance Z_L seen from A
AR	impedance of 80% length of line from A	θ°	line angle 63.5°
φ	maximum torque angle of Mho relay = 45°	*AD*	relay setting
O	origin of Mho-circle mho circle passes through A.		

Fig. 42.17 (Example 42.1 *b*). Line characteristic and Mho-relay setting on *R-X* plane.

Draw line *AD*, line of maximum torque at angle φ equal to 45° (given).

Draw a circle passing through points *A*, *R* with *AD* as axis. Point *D* is fixed as follows :

$$\cos(\theta - \phi) = \frac{AR}{AD}$$

$$AD = \frac{AR}{\cos(\theta - \phi)} = \frac{5.98}{\cos(63.5° - 45°)} = \frac{5.98}{0.948} = 6.32 \text{ ohms.}$$

Hence setting *AD* of mho relay = 6.32 ohms. The circle of mho characteristic with this setting passes through *A* and *R* (Refer Fig. 42.17).

Example 42.2. Effect of Fault Resistance. *Consider the plain impedance relay and mho relay as set in Example 42.1 for protection 80% of line AB. Given a symmetrical phase to phase fault at F at a distance 60% from A. Fault resistance is 20 ohms. Indicate the fault point on R-X* diagrams and state whether the relays operate or not.

Solution. Convert fault resistance for secondary side.

$$\text{Fault Resistance Secondary} = \text{Fault Resistance Primary} \times \frac{\text{CT Ratio}}{\text{VT Ratio}}$$

$$= 2.0 \times \frac{400}{1} \times \frac{110}{33{,}000}$$

$$= \frac{8}{3.0} = 2.6 \text{ ohm (Secondary)}$$

Indicate point *F* on line *AB* at 60% of *AB*

$$AF = \frac{60}{100} \times 7.47 = 4.49 = 4.5\ \Omega.$$

Draw *FX* parallel to *R* axis.

$$Fx = 2.6 \text{ ohms (Fault Resistance)}$$

Refer Fig. 42.16 and Fig. 42.17.

From Fig. 42.16, the point *X* is outside the circle. Hence plain impedance relay does not operate. (Under-reach : reads less impedance).

From Fig. 42.17, the point *X* is inside the circle. Hence Mho type distance relay operates.

Conclusion

1. The mho characteristic provides margin for the arc resistance than the plane impedance characteristic.

2. The area of mho characteristic being less than the impedance characteristic, the mho characteristic gives better stability.

Example 42.3. Setting of a Distance Relay. *A 110 kV of 35 km length is protected by Impedance Relay. The first stage of distance relay protects 90% of the line. Calculate the setting of impedance relay and draw the characteristic of line and the relay on R-X plane. Neglect the influence of arc resistance.*

The line impedance is 0.24 + j 0.41 ohms per conductor per km.

CT ratio is 300/1 A and VT ratio is 100 kV/100V.

Solution. Line impedance

$$= 0.24 + j0.41 \text{ ohm/km.}$$

Line angle (Refer Fig. 42.16)

(Assumed the same for phase faults and earth fault).

CT ratio $= 300/1 = 300$

VT ratio $= 100{,}000/100 = 1000$

Step 1. Calculate line impedance referred to secondary

$$Z_s = Z_p \times \frac{\text{CT Ratio}}{\text{VT Ratio}}$$

For 90% line of 35 km length,

$$Z_p = 0.9 \times 35 \times (0.24 + j0.41).$$

$$= 7.56 + j12.9 \text{ ohms per conductor}$$

$$Z_s = (7.56 + j12.9) \times \frac{300}{1000}$$

$$= 2.268 + j3.87 \text{ ohm secondary.}$$

Step 2. Impedance Diagram (Refer Fig. 42.16 for guidance). Draw a line *AB* at an angle $\theta = 60°$ to *R* axis. Plot point *R* at $R = 2.268$ and $jX = 3.87$.

Draw a circle with centre *O* at *A* and radius $AR = \sqrt{(2.268)^2 + (3.87)^2}$. This circle represents characteristic of a plain impedance relay to protect 90% of the line.

QUESTIONS

1. With the help of neat sketches describe the principle of a current comparator and a voltage comparator used in distance protection.
2. Discuss the use of multi-output comparators in static distance protection. Explain how oval and quadrilateral characteristics can be obtained on *R-X* plane.
3. With the help of a block diagram explain the functioning of a static distance relay.
4. In a distance protection scheme, the line CT has a ratio of 300/1 A, the line VT has a ratio of 33,000/110 V. The line impedance is 0.24 + *j*0.41 ohm per conductor per km. Length of line is 25 km.
   Draw *R-X* diagram indicating the line characteristic with reference to secondary.
   Indicate the circle of plain impedance characteristic to protect 80% length of line (Neglect fault resistance).

5. Indicate on an R-X diagram, the following (select suitable scale, point A at (0, J 0).
   (a) Point $R = 1\ \Omega\, jX = +3$
   (b) Point $R = 1, jX = -1$
   (c) Line impedance $AB = 2 + j4$
   (d) Fault resistance at the end of line AB equal to two ohms.
   (e) Mho characteristic with maximum torque angle 53° and radius 3 ohms.
   (f) Plain impedance characteristic to protect 80% of line AB

   Explain the advantages of Mho-characteristic over the plain impedance characteristic. Quantities given refer to secondary side.
6. **Power-Swings.** Explain with the help of neat sketches the phenomenon of power swings in transmission system with particular reference to its influence on distance measurement.

   Describe the blocking features adopted in distance relays to offer selective blocking under power swing conditions.
7. **Lines with series Capacitor.** State the function of series capacitors in long transmission lines. Discuss the difficulties in distance measurement with application of series capacitors. Explain the effect of series capacitor on impedance characteristic drawn on R-X plane. Explain the remedial features provided in distance relay schemes to protect such lines.
8. Explain the following (any two)
   (i) carrier acceleration
   (ii) carrier blocking
   (iii) mho characteristics
   (iv) directional mho characteristics
9. Discuss the errors in distance measurement in double-in-feed lines. State the remedial measures in distance protection schemes for such lines.
10. Explain the requirements of distance protection schemes of long EHV transmission lines. State the merits of static distance relays. Illustrate the features of any static distance relay by means of simplified block-diagram.
11. Explain effect of intermediate infeed from a Teed line on the distance measurement of transmission line.

43-A

Important Assorted Topics and Static Protection Schemes

Insulation, Reliability, Testing
Electrical Noise — Shielding — Guards — Grounding — Over-voltages — Protection — Reliability — Tests for reliability.
Static Protection Schemes
Static protection of Medium Motors and Large Motors — Static Protection of Busbars — Disconnection of Mains Supply by Static Schemes.
Back-up protection, Centrally Coordinated Back-up, protection Signalling
Breaker Back-up — Use of Microprocessor — Computer based centrally coordinated Back-up Programmable Equipment for relaying, protection and control — Principle of centralized back-up — Post fault control — Communication Links for protection signalling — Digital Message System — Fibre Optic Data Transmission.

INSTALLATION, RELIABILITY AND TESTING OF STATIC RELAYS

43.1. COMBATING ELECTRICAL NOISE AND INTERFERENCES

Any disturbing signal which interferes or disturbs the electronic measurement/signal/parameters is electrical noise. All electronic circuits and their installations should be with the noise below acceptable level. This is very important for accurate functioning and reliability of static relay functioning. Conventional electromagnetic relays do not have such a problem. Relaying and control installations for static devices should be designed with particular attention to noise and transient over voltages. The effect of noise and transient over-voltages is two-fold.

(i) error in measurements (ii) maloperation.

The noise can be caused by the following :

— Interfering external signals in the form of electromagnetic radiation or waves, *e.g.* solar waves, radio waves from transmitting stations, electromagnetic waves caused by sudden current changes in a remote electrical circuit, a passing electrical locomotive may cause an error in electrical measurement, a radio voice is distorted by interference from neighbouring station, switching of high voltage line sends a electromagnetic radiation, sparking or corona discharge at a remote point causes disturbance in sensitive voltage measurement.
— Lightning and Switching Surges on primary side of CT's and VT's get reflected on secondary in form of voltage spikes.
— Drifts in electronic apparatus beyond their limit of stability.
— Imperfect connections of fixed wires or connectors leading to minute sparking. Corrosion/wear/imperfection of working joints.
— Device noise depending upon characteristic of resistors, capacitors, semi-conductors as affected by temperature, humidity, loading.

The noise tends to spread throughout an electronic system because of electrical relationship between circuit conductors, enclosures, chassis and ground connections through conductive, capacitive and inductive couplings. Electromagnetic radiation causes voltage gradient between two conductors although not connected physically.

Adjacent conductors are coupled electrostatically. An inherent capacitance exists between, ground, conductors and chassis, shields, enclosures. Thus the voltage change occurring in one conductor causes a change in other conductor, proportional to the capacitance between them and length of conductors in parallel.

Every conductor has a resistance. Change in current produces change in voltage drop, electromagnetic field from parallel conductor induces current and subsequent voltage drop. A sudden change in current in neighbouring conductor produces a voltage spike in the circuit.

Shielding refers to enclosing the conductors or apparatus in enclosure almost completely. Shielding reduces the capacitance between the circuit and outside space. The most effective shield is continuous metalized plastic solid shielding is more effective than braided shielding. Effectiveness of shielding increases with the thickness of the shield and conductivity. Solid copper or silver or aluminium or similar non-magnetic material is effective against a electrostatic and electromagnetic interference. The shield should be insulated from the equipment and equipped with a drain wire for single points grounding.

Grouping several signal conductors within one shield is permissible, if all the signals have same ground point and capacitance between them is acceptable. When several shielded conductors are combined in a cable, each should be covered with insulation.

Placing shielded cable within a metallic conduit is useful. The conduit of good conductivity and thickness is preferable.

Grounding means connecting to earth by a conducting path.

— *Equipment Grounding* : Connecting non-current carrying conductor to earth.

— *Chassis Grounding* : Chassis is used as a reference earth. Chassis may not be connected to earth.

— *Floating Ground* is a reference ground which is not earthed.

— *Signal Ground* is a point within the circuit to which all signals within the circuit are referenced.

— *Uniground or Single point ground.* Single point of electrical system connected to earth to eliminate noise currents.

Signal cables may usually run near each other without interference. However wires carrying a.c. or d.c. power should be separated by at least 10 cable diameters. *Also twisting a pair of leads reduces both inductive and capacitive coupling and interference* (Fig. 43.6.)

43.2. TRANSIENT OVERVOLTAGES IN STATIC RELAYS

During the early period of use of static relays in protection of EHV networks (1960-70), a large number of failures and maloperations of static relays were reported. After investigation, the cause was attributed to high transient overvoltages in relays circuits. The transient overvoltages were measured. Their magnitude was observed to be even of the order of 12 kV, 20 kV peak, on secondary side *i.e.* in relay circuit. After such investigation, necessary research was conducted to find the causes and remedies of transient over-voltages in secondary circuits. These aspects are discussed below :

1. Source of Transient Overvoltages in Static Relay Circuits

There are following three origins of transient overvoltages in static relays circuits connected to the secondaries of CT's and PT's in EHV systems :

1. Transient overvoltages reflected from transient overvoltages in the primary circuits of CT's and VT's. In primary circuits, the overvoltages occur due to lightning, switching, sudden change in circuit conditions, etc. These get reflected to the secondary side.

2. Transient overvoltages generated in control equipment due to breaking of inductive currents in relay circuit, trip circuits etc.

3. Transient overvoltages generated within static relays.

The transient overvoltages of category (1) above, are due to operation of circuit-breakers and isolators. In EHV systems, these overvoltages predominate overvoltages due to lightning. During every switching operation overvoltage occur. The worst cases being operation of unloaded lines by slow operating isolators. The amplitude of such overvoltages can be between 10 kV to 20 kV peak, measured between cable core and earth, when cable is laid on earth and connected to capacitor type voltage transformer. Screened cable or shielded cables, with shield grounded at both the ends are used to reduce to transient voltage to the extent of a few per cent of their prospective value (value, without shields). The frequency of damped sinusoidal oscillations varies widely between 50 kHz to 1 MHz. The source impedance have values between 200 to 300 ohms. The design of circuit-breakers and isolators affect such voltages. A 'train of transients' occurs during the arcing time while opening as well as closing the breaker. The train comprises pulses in the range of 350-400 pulses/second in many cases.

The group (2), mentioned above give transient having steep wave front. Most of the transient overvoltages originating within the control equipment is due to breaking of small inductive currents such as those in auxiliary relays. Such transients have high amplitude and high frequency. A number of restrikes may occur between switching contacts. Transient voltages generated within the relay (group 3 above) have relatively low amplitude and energy. However, they can destroy or disturb certain sensitive components in the static relays.

A usual transistor can be damaged by energy of 10^{-5} to 10^{-3} watts, integrated circuit by energy of 10^{-4} to 10^{-8} watts. Transient overvoltages also arise due to rapid changes in current in wire-wound resistors.

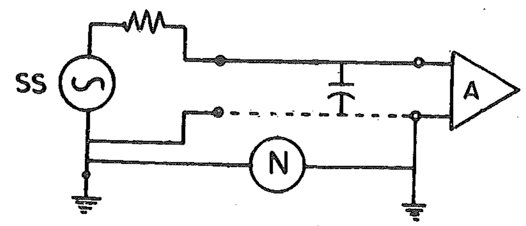
The characteristic of transient voltages include the following :

(*i*) frequency, rate of rise (*ii*) amplitude

(*iii*) energy content (*iv*) source impedance

(*v*) repeat frequency

Fig. 43.1 to 43.5 — Comparison of Shielding, Grounding and Twisting Techniques



SS = Signal source,
A = Apparatus,
G = Ground,
N = Noise Signal,
S = Shield.

Fig. 43.1. Bad method of connection :
Ground return earthed at apparatus end and signal end.
Signal lead and return lead parallel.
Electromagnetic radiation and closed loops cause maximum interference.

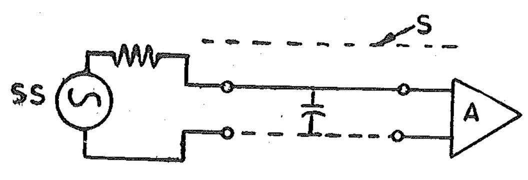


Fig. 43.2. Using single shielded signal lead. Return path by shield grounded at both ends. Shield capacitively coupled to lead, hence can give noise.

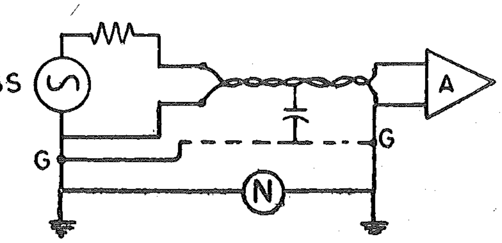


Fig. 43.3. Use of twisted pair of signal lead and return lead improves radiated noise but ground loop capacitive coupling continues.

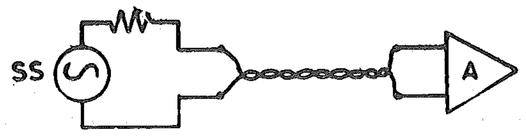


Fig. 43.4. Twisted pair of signal lead and floating apparatus input gives considerable noise immunity.

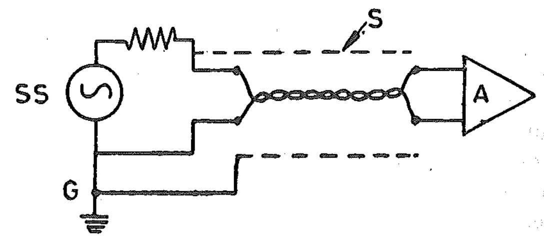


Fig. 43.5. Use of twisted pair of signal lead and return lead, connecting the shield to low side of apparatus floating input reduces shield to lead capacitors. This method is recommended.

43.3. PROTECTION OF STATIC RELAY CIRCUIT

Extensive investigations and analysis of data and experience on electric system circuits show that relay control circuits can be effectively protected against transient and surges by several different methods or techniques.

(*i*) Separation
(*ii*) Suppression at source
(*iii*) Suppression by termination
(*iv*) Suppression by shielding
(*v*) Suppression by twisting
(*vi*) Radial Routing of control cables
(*vii*) Buffers.

Circuit protection by *separation* refers to both physical and electrical techniques. *Physical separation* between quiet and noisy circuits is an effective means of noise control critical circuits. Though mutual capacitance and mutual inductance are logarithmic functions of distance small increases in distance may produce substantial decreases in interaction between circuits.

Routing of control circuits perpendicular to noisy circuits is another effective physical precaution. An example of this would be placing a cable duct run perpendicular to a high-voltages bus. This places any parallel runs between the control circuit and the bus at the maximum practical realizable distance.

Another effective measure in surge control is the grouping of circuits that have comparable sensitivities. Low-energy-level circuits should be grouped together and physically displaced as far as practical from power circuits.

Electrical separation is another useful principle in segregating circuits. In surge control, this appears in the form of inductance discriminatory applied to block conduction of high-frequency transient into protected regions.

Another form of electrical separation is provided by zener diode. It allows conduction, but blocks the flow of current in the other (below the zener voltages level). Also, transformer isolation is an effective method of providing a common mode barrier between segments of a system.

To support transients of surges at the source, either resistor switching or parallel clamping techniques are used.

Isolators and circuit breakers can be equipped with resistors that are inserted during operation of the device to limit the transient voltages to comparatively low values. Economy may occasionally dictate this as a means of restricating the surge level in a sub-station as opposed to other methods.

The surge associated with coil interruption can virtually be eliminated by paralleling the coil with a zener diode. This extends the release time, however, and where this is significant to the application, a varistor may be used instead of the zener diode. The surge permitted by the varistor is higher than that for the zener diode, but its limiting action is satisfactory.

The surge associated with extreme a.c. saturation of a current transformer can also be reduced by a voltage-limiting device across the secondary. Silicon carbide devices have been used for this protective function.

An effective termination that reduces the input impedance at high frequency and has little effect at 50 Hz or on d.c. is a *small capacitor*. It neither forces a higher input energy nor produces heat of its own. A widely used capacitor is a 0.5 mF, 1,500 V d.c. oil-filled type. It limits a 2,500 V, I-megacycle surge with 150-ohm source to less that 35 V. Short leads to the capacitor imperative.

When suppressing transients *shielding methods,* a signal lead shielding with one or more grounds has the effect of increasing the capacitance to ground of the signal lead.

Grounding a shield at both ends allow shield current to flow. Shield current resulting from magnetic induction will tend to cancel the flux that created the shield current. The net effect of the shield on the signal lead is to reduce the noise level. An exception to this is that current flowing in shields not produced by flux linking the signal lead will cause the surge or noise voltage on the signal lead to be higher than it would be if there were no shield.

"Twisting" for surge suppression is achieved by measures that cause the "signal" and "return" leads to occupy essentially the same space, thereby minimizing the effect of differential-mode coupling. Shielded twisted-pair conductors are required for low-energy level circuits routed outside a panel.

As regards radial routing of control cables for surge protection, circuits routed into the switchyard from the control house should not be looped from one piece of apparatus to another in the switchyard with the return conductor in another cable. All supply and return conductors should, in other words, be in a common cable. This is to avoid the large electromagnetic induction possible because of the very large flux loop such an arrangement would produce.

Another effective measure applied to show and desensitize a circuit is a *buffer*. This buffer can accommodate a test source operating at 1 Mhz having 150 ohm source impedance placed directly across the input (differential mode) and having 2,500 V (open circuit) first peak, decaying to 1,250 V in six microsec or more, without the transistor turning on or any element being damaged. It can, with the same results, stand a sustained 7 V d.c. input, or high-level d.c. input voltage of sufficient duration to produce a 4,000 microsec-V product-for example 200 V for 20 ms.

Adequate buffering of low-energy-level circuits greatly decreases the susceptibility of static relays to surge damage or misoperation and, in general, eliminates the need for shielding of circuits inside a relaying panel.

43.4. RECOMMENDED PROTECTION PRACTICES FOR STATIC RELAYING EQUIPMENT*

The recommendations are as follows : They apply particularly to HV and EHV stations utilising static relaying.

1. All current, potential and exposed D.C. leads entering a panel or cabinet shall be terminated by 0.5 microfarad capacitors keeping total capacitor loop lead length as short as possible. A total loop length of 18 inches may be used as a guideline. Thyristor trip circuits must be equipped with TP-2 components (2 winding reactor and zener) or suitable substitutes and a 0.5 microfarad capacitor must be connected between the negative side of the zener and ground.

2. Where low impedance (such as that offered by a zener (diode) exists between an exposed lead and a surge protective capacitor applied to another lead, the capacitor may be omitted from the exposed lead.

3. Circuits entering the panel that are not subject to direct switchyard exposure but are in close proximity to extremely noisy circuits in a cable tray for example, must be treated carefully if they supply low energy level inputs in the panel. The circuit external outgoing and return circuits. The shield should be grounded at both ends.

4. Circuits entering the panel that are subject to direct switchyard exposure that cannot accommodate the 0.5 microfarad capacitor because of the time delay introduced, or for any other

* *Courtesy* : Westinghouse Electric Corporation, U.S.A.

reason, must their surge voltage be controlled by special cable routing or surge generation must be limited at the source to help the surge levels at the panel terminal blocks to the limits stated under (D) below.

5. All cables entering the static relay panel from the switchyard or connected to circuits entering the switchyard shall

(*a*) be shielded (with metallic shield or sheath)

(*b*) have sufficient cross-section in the shield (or metallic sheath) to sustain the maximum 60 hertz current to which it will be subjected to ground fault conditions.

(*c*) have the shield grounded to the common ground mat at both ends of the cable and preferably at intermediate points also. If a common ground mat does not exist between two ends, then means should be taken to assure a low impedance connection between the two ends of the cable. This may be accomplished by connecting the separate mats with one or more cables having sufficient cross-section to handle resulting fault and surge currents.

(*d*) have conductors in pair (outgoing and return conductors) in the same cable. While tri-axial cable affords distinct theoretical advantage for the circuit between a carrier set and tuner (carrier return circuit is grounded at only one point and is eliminated as a possible conduction path for interfering surges), it is felt that its use is not mandatory in EHV stations.

6. Coils of all electromechanical auxiliaries used on the panel must be equipped with a varistor or equivalent surge suppressing means in parallel with the soil.

7. It should be emphasized that the relay designs themselves include zener diodes, capacitors, winding isolation etc. to minimize susceptibility of a static relay to surge damage or misoperation.

8. The fundamental protection philosophy is to (1) provide a low impedance path to ground for high frequency current flow caused by voltages appearing on exposed leads and (2) to minimize the magnitude of these voltages by proper treatment of the loads.

9. The practices outlines here related to static relaying panels and the leads connected to them but apply equally to isolated static devices where surge exposure exists.

10. **Laying of Control, Protection and Measuring Cables.**

The main current in the control cable conductors being low, these cables may be laid in a common duct, without separation. However they should be separated from power cables.

Highly sensitive measuring cables are sometimes laid in separate steel pipes totally away from other cables.

11. **Grounding of Cable Trays, Ducts.**

All the cable trays, racks and metallic ducts should be grounded by connecting at each end to station earth-mat. The adjacent cable trays should be bridged by copper jumpers, to retain continuity of earthing.

43.5. TESTING OF STATIC RELAYS WITH REGARD TO OVER-VOLTAGE TRANSIENTS

The IEEE Power system Relaying Committee has proposed certain tests on static relays as regards their sensitivity to overvoltage transients. British Electric and Allied Manufacturers' Association Ltd. (BEMA), England has issued a publication (No. 219), titled "Recommended Transient Voltage Tests Applicable to Transistorised Relays", proposing an impulse test with limited sources energy. The test consists of subjecting the relay an impulse voltage of 5 kV (1.5 kV) with 1/50 μs wave and energy 0.5 W both in common and transverse modes. Three positive and three negative pulses are applied. Source impedance of impulse generator is 500 ohms.

Static relays should withstand the following design tests :

1. 1500 volts RMS, 60 hertz of 2000 volts d.c. applied between ground and a common point to which all terminals are connected for 1 minute without failure.

2. An input having a volt-time product of at least 4000 microsecond-volts may be applied between energized logic inputs and negative (or positive) without operation (operation being defined as any change of state). An example of this input is 40 volts D.C. applied for 200 microseconds at higher voltages, no less than 65 microseconds' duration is permissible.

3. Surge withstand capability test for 1 MHz applied by a surge generator having an open circuited voltage of 2500 to 3000 volts first peak, decaying to 50% of first peak in 6 microseconds. The surge generator has 150 ohms internal impedance. The surge is applied common mode between signal, current, voltage or power supply leads and chassis. It is also applied differential mode between input logic, output logic or power supply leads and common. The surge is applied at least 50 times per second for not less than 2 seconds without failure, operation or change of calibration.

4. 7 volts positive D.C. sustained between logic circuits inputs and negative without operation. Tests 2, 3 and 4 are applied with the relay energized at 100% voltage and with 75% of nominal CT current.

43.6. RELIABILITY, DEPENDABILITY, SECURITY

Reliability of a product is related with its quality during the total working life. It is usually expressed in terms of the failure rate of individual components of Mean Time Between Failures (MTBF) of the equipment and installation. The ability of protection equipment to operate can be disrupted in three ways :

— Maloperation *i.e.* false tripping in absence of primary fault.

— Incorrect separation or undesirable tripping during a primary fault, *e.g.* back-up protection operates first and trips a circuit-breaker which should not have been tripped. This leads to power failure affecting larger areas.

— Failure to operate (*i.e.* does not trip even on fault when it was supposed to). The back-up protection is provided for this possibility.

The reliability is further expressed in terms of Dependability and Security.

Dependability (Trust worthiness) assures that the protection equipment will operate correctly in the event of a primary fault (trip selectively).

Security assures that the equipment will not operate unless there is a primary fault.

In general the reliability depends on a Design of Protection Scheme, relay and also quality of components, manufacturing technique.

Design Reliability includes apart from the design of the relay itself, the design of complete scheme, other relays, the circuit which form the protection system. The *equipment reliability* is expressed as a probability which can be determined by careful evaluation of the circuit in relation with failure rates of components.

Technical Reliability is subject to external influences and generally declines with time.

Ensuring Higher Design Reliability

A complete protection scheme should be considered. This includes

— CT's , VT's

— Batteries, auxiliary supplies, battery chargers, overload trips.

— All wiring between measuring devices, auxiliary sources, relay and circuit-breaker, auto reclosure and auxiliary relays.

— All main and auxiliary relays.

— All terminals

Communication Channel (PLC or Pilot wires)

Trip circuit

Circuit-breaker, its operating mechanism and control circuit, main current circuit, insulation.

The Application Engineer and Station Designer should have overall concept of the requirements of various components. Each component should be reliable to ensure overall reliability.

Factors affecting the Design Reliability of Complete Protection System

- — choice of suitable CT's and VT's with reference to transient conditions
- — behaviour of CVT's during transient condition for application to high speed distance relays
- — behaviour of d.c. supply unit in protection equipment during battery voltage dip
- — behaviour of the protection in the presence of overvoltages, noise, interference, etc.
- — behaviour of protection during transients on measuring and control wiring
- — behaviour of protection during overages
- — arrangements, shielding arrangements.

For most of these influences IEC recommendations are available. The internal voltages in relay are limited by appropriate design features in the relay.

The external factors are taken care of by Station Designer. The induced voltages in secondary circuits must be within specified limits and IEC test voltages.

Ensuring Higher Technical Reliability

The following aspects are considered to ensure technical reliability (which does not depend on design but depends on quality of components as affected by external influences.)

- — environmental and operating conditions
- — material and components used in the circuit
- — failure analysis
- — manufacture, testing, quality control
- — operating experience.

Environmental and Operating Condition Tests

These include the following :

- — Temperature Tests, Climatic Tests, Thermal shock Tests (– 185°C to 200°C), temperature cycling tests (– 185°C to 300°C) carried out as type tests on components, sub-assemblies, complete relay.
- — Environmental tests : salt atmosphere or spray (25°C to 71°C) performed as type tests.
- — Vibration Tests, shock tests.

Choice of Components

The rigorous acceptance testing of active components of static relays includes 100% acceptance tests on active components (diodes, transistors, IC's) and random testing on other components.

Some tests on electronic components are mentioned in Table 43.1.

Rigorous Tests of Complete Relay*

These include design tests, reliability tests, type tests and routine tests, maintenance and site tests.

Automatic On-line Testing of Protection Scheme

The testing of protection schemes (such as generator protection) comprises the checks on all relays in the protection schemes *viz.* voltage, current, frequency, directional, differential, etc. In each case, the pick-up value of each relay for each phase should be measured. Automatic test sets have been developed for static protection schemes. The test equipment *measures* the pick-up values *regardless of service current* and these values are displayed and printed out digitally. The printed values can be relaxed to control centre for monitoring. Modern microprocessor based static relays have self-checking feature (watch dog).

Table 43.1
Tests on Components, Sub-assemblies, Complete Relays

	Component	*Sub-assembly (Modules)*	*Complete Relay*
Altitude			*
Dew point		*	*
Flammability	*	*	*
Moisture resistance	*	*	*
Resistance to solvents	*		
Salt atmosphere	*	*	
Salt spray			*
Seal, gross leak		*	*
Soldering heat	*	*	
Terminal Strength			
Acceleration	*	*	*
Mechanical shock		*	*
Vibration, fatigue		*	*
Vibration, noise	*	*	*
Vibration, variable	*	*	
Frequency	*	*	*
Seal, fine leak	*		
X-Ray, film	*		
X-Ray, Real Time	*		
Insulation Tests	*	*	*
Maloperation Tests		*	*
Development Tests	*	*	*
Type Tests		*	*
Routine Tests	*	*	*

Section II. SOME STATIC PROTECTION SCHEMES

43.7. STATIC RELAY FOR MOTOR PROTECTION

The introduction of static relay using integrated circuits now allows compact, combined protection relays. A single unit can combine about six functions of motor protection. This results in reduced space, reduced installation time, lower total cost. The relay also gives better characteristic and reduces burden on CT's.

Motor Protection Relay

(*Courtesy* : Brown Boveri, Switzerland)

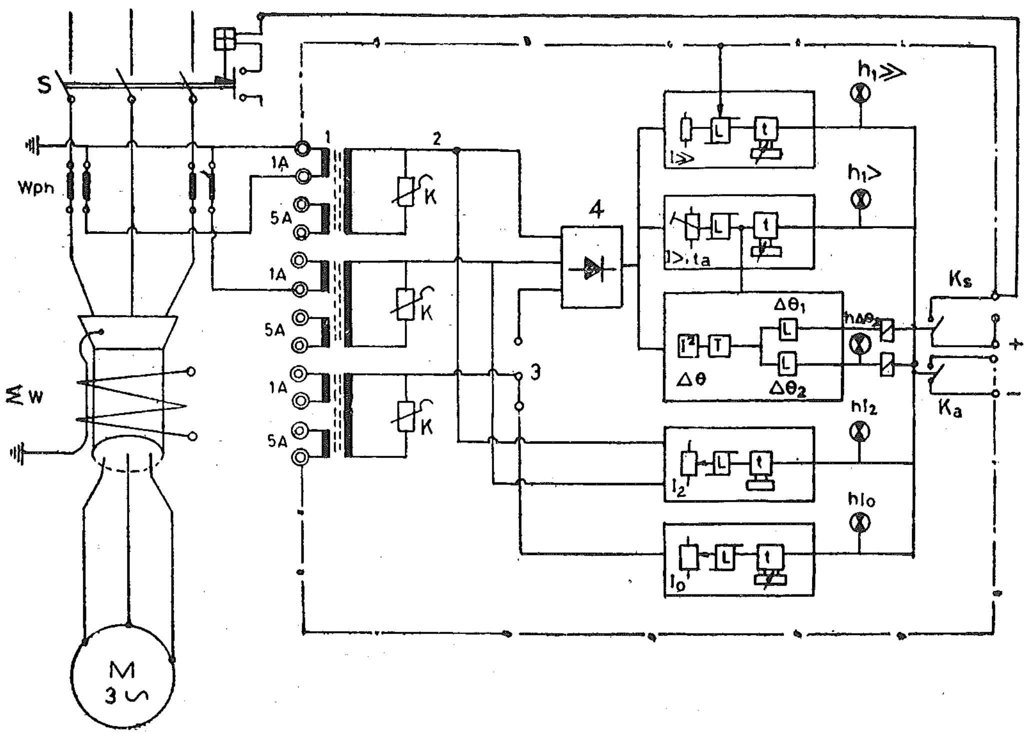
The relay of this type protects three phase induction motors against interphase short-circuits, prolonged starting, locked rotor, overloads, unbalance and earth faults. Similar type of relays are available for protection of over-current and overload protection of transformers and cables. These relays have following features :

- — Only two or three phase currents needed as measurement inputs.
- — Good match for all kinds of motors due to wide range of adjustments.
- — Separate indication for individual function (local and/or remote).

— Two-stage overload protection with thermal facsimile which is retained even if the auxiliary supply fails.

— Can be flush mounted on switchgear or protection panel ; or can be arranged on separate racks.

Ref. Fig. 43.6 giving the block diagram of static motor protection relay for medium, medium large motor. The core balance CT (Σ W) slip over current transformer (Refer Sec. 27.9) is for giving output in terms of zero sequence current ($3I_o = I_R + I_S + I_T$). This output $3I_o$ is useful for sensing earth fault. Due to lower burden of static relay ; cross-section of core of core-balance CT is comparatively less and a compact core balance CT can be used with better accuracy and sensitivity of earth-fault protection (Ref. Sec. 31.7). The two phase CTs (*Wph*) are installed in the supply connections (generally inside the control panel or switchgear unit). Their secondaries are connected to the input intermediate CT (1) of the Static Relay. The output of intermediate CT's given to rectifier



I_0 = Zero sequence prot.
S = Motor circuit-breaker
W_{ph} = Phase current transformer
ΣW = Core balance Z.S. CT (Ref. sec. 27.9)
M = Asynchronous motor
1 = Input current transformer
2 = Burden of CT adjustable in ten steps
k = Setting factor
3 = Selector switch
4 = Rectifier
$I >>$ = Short-circuit protection
$I >$ = Protection against prolonged overload
t_a = Time lag
$\Delta\theta$ = Overload protection
$\Delta\theta_1$ = Warning-stage of overload protection
$\Delta\theta_2$ = Tripping stage of overload protection
I_2 = Squaring Element
T = Interactor of Thermal Facsimile (Replica)
I_2 = Unbalance (negative sequence) Protection
$h_1 \gg h_2$ etc. = Visual signals
K = Setting
K_s = Indicator Contactor (Overload Warning)
K_a = Tripping Contactor
L = Level Detector and Trigger.

Fig. 43.6. Circuit and Functional Diagram of a Motor Protection Relay
Courtesy : Brown Boveri.

bridge (4). The output of rectifiers is given to the measuring circuit comprising following sub-circuits depending upon requirements.

— short circuit $I \gg$) circuit without time delay
— prolonged starting ($I > t_a$) circuit with time delay
— Overload circuits $\theta_1 \cdot \theta_2$ with warning and tripping stages. The characteristic corresponds to motor heating curve.
— negative phase sequence circuit (I_2) for unbalanced loading
— zero-sequence circuit (I_o) connected to core-balance (slip-over) CT.

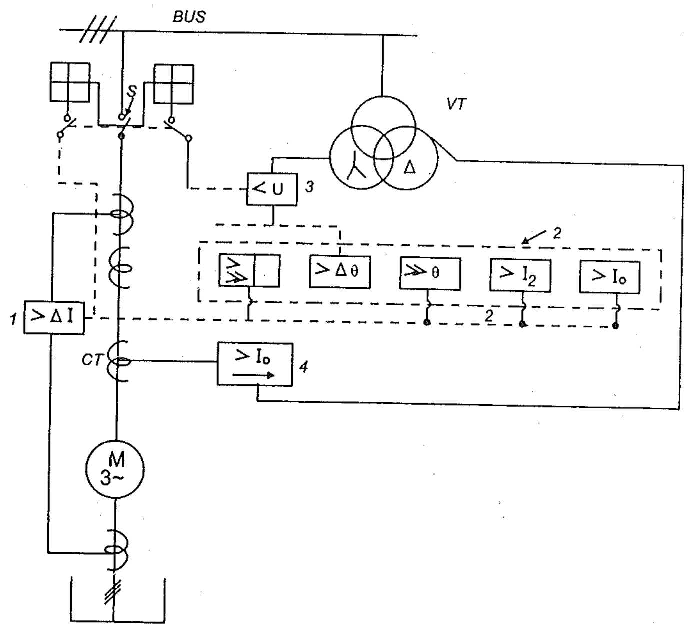
Light emitting diodes (LED) are provided for local indication of each function (or floating potential contact with remote indication)

The warning signal closes contactor K_s sounding a local/remote alarm. The tripping is initiated by closing of contractor K_a.

Block diagram of a static relay for large high voltage motor protection is given Fig. 43.7. This incorporates

— Differential relay (1)
— combined overcurrents (> >), overload(>), unbalance ($> I_2$), a earth fault ($> I_o$) relay
— directional earth fault relay $\left(\begin{matrix} > I_0 \\ \longrightarrow \end{matrix}\right)$

All these functions are provided in a single relay unit. Units for several motors can be arranged on one single rack.



1. Differential Relay
2. Combined overcurrent, overload, unbalance, earth-fault Relay
3. Undervoltage Relay
4. Directional Earth-fault Relay
5. Circuit-breaker and other symbols as in Fig. 43.2.

Fig. 43.7. Functional Block Diagram of a large high-voltage Induction Motor Protection Scheme.

43.8. STATIC BUSBAR PROTECTION BASED ON DIRECTIONAL COMPARISON

We will recall, the busbar protection can be based on different principles such as

— Busbar Protection by Over-current Relays. This can be adopted for networks where the in-feed is not clearly defined and where the outgoing feeders to loads are not subject to reverse feed.

— Busbar Protection by Distance Relays of incoming lines

— Busbar protection by Differential Relays

— Busbar Protection by Directional Interlock

The static Busbar Protection schemes have following advantages :

— Modular design. Required modules can be plugged-in accordance with the protection scheme. Hence the design is simple and easy to operate.

— Low burden on Main CT's. Hence problems arising out of CT saturation are reduced.

— Measurement can be independent of CT saturation.

— Intermediate CT's can be decentralised (provided in a separate module with each relay).

Ref. Fig. 43.8, giving functional block-diagram of static busbar protection based on directional comparison.

The direction of currents in all outgoing feeders (II_1, II_2) is compared with the directional of differential current. During internal busbar fault (SC), all these currents flow in the same direction (Towards Busbar in Primary).

If this condition persists for a definite period (or the order of milliseconds) the internal short-circuit is confirmed and the relay trips. Additional conditions for tripping include magnitude of feeder current and their sum. These conditions increase the security of protection.

Ref. Fig. 43.8, the pulse shaper D converts sinusoidal signals into rectangular pulses-D_p converts only positive half cycles and D_N converts only negative half cycles (into rectangular pulses).

F_p and F_n are NOR gates for positive half rectangular pulses and negative half rectangular pulses respectively. The three rectangular signals received by F_n comprise negative half-wave pulses from three D_N elements. These are for out-going feeder II_1 outgoing feeder II_2 and difference between II_1 and II_2 as can be observed from the figure. Let us make truth table for the logic of NOR gate F_n, X being output of F_n.

II_1	II_2	$(II_1 - II_2)$	X
1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1

From the truth table, NOR gate F_n gives output (x = 1) when three inputs II_1, II_2 and ($II_1 - II_2$) are (0). *i.e.* when three negative half pulses are simultaneously absent (conditions 0).

Similarly NOR Gate F_P gives output (Y = 1) when three input positive half, pulses (II_1, II_2, $II_1 - II_2$) are simultaneously absent (condition 0)

The output X of F_n and Y of F_P is given to OR gate G. The truth table of G is as follows :

X	Y	Z
1	0	1
0	1	1
0	0	0

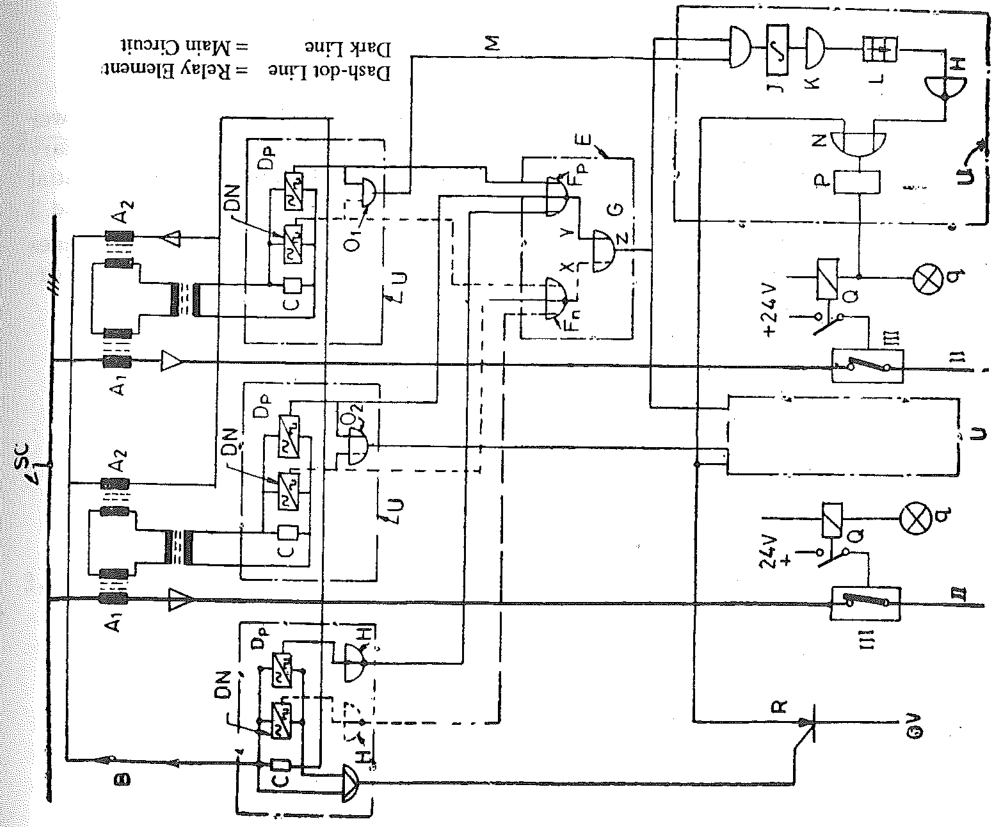


Fig. 43.8. Functional Block-diagram of static Busbar Protection, scheme Based on Directional Comparison.

I = Busbars
II_1, II_2 = Outgoing Feeders
III = Circuit-breakers
A_1 = Main CT
A_2 = Intermediate CT
B = Common Burden
Δ = Direction of Normal Current
Δ = Direction of Intend fault Current
C = Shunt
D = Pulse shaper
D_p = Shaper of Positive half wave
D_N = Shaper of Negative Half wave
E = Central Unit Directional Comparison
F = NOR Gate for the positive half
F_n = NOR Gate for the negative half
G = OR Gate (combination of F_p and F_n)
H = Inverters
J = Integrator (5 ms)
K = Trigger
L = Drop-out Prolongation (Delay Circuit)
M = Tripping Line
N = AND Gate
O_1, O_2 = Tripping Inter-locks
P = Amplifier
Q = Tripping Contactor
q = Trip Indication
R = Trip Release
S = Digital Signal Directional Comparison
S_c = Short-circuit
U = Feeder Measuring Elements.

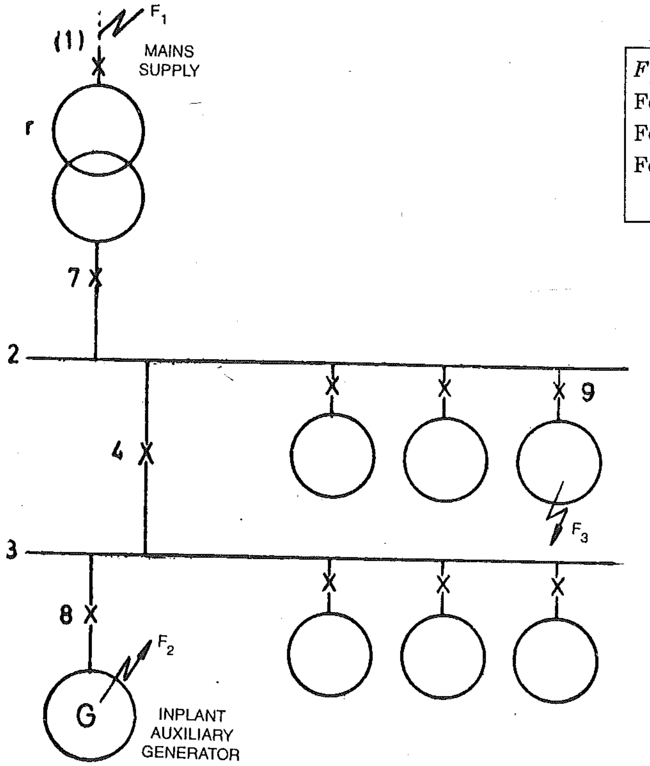
when any of the inputs X or Y are high (x = 1 or y = 1), the output is high (Z = 1). When positive half cycles derived from feeder currents and difference in feeder currents are simultaneously present, the control unit of directional comparison E gives output to trip release R *via* feeder measuring unit U.

AND Gates O_1 and O_2 provide additional interlock conditions *via* measuring element U for trip release R.

43.9. DISCONNECTION OF MAINS SUPPLY FROM INPLANT AUXILIARY SUPPLY DURING SYSTEM FAULTS

(*Courtesy* : Brown Boveri, Switzerland)

Many industrial plants have their inplant generating station and need uninterrupted power for the industrial process. The power is taken from Mains Network as well as inplant auxiliary generator (generally driven by gas turbine). The segregation of essential loads and non-essential loads is illustrated in Fig. 43.9. During system faults (say F_1). The voltage of bus-bars 2 and 3 drops down and the supply of essential loads and non-essential loads is disturbed. Hence, it becomes necessary to disconnect the mains supply very quickly during fault on mains (F_1) by opening circuit-breaker (7) and bus-coupler (4).



F_1, F_2, F_3 = Possible Faults
For $F_1 \rightarrow$ Trip (7) and (4)
For $F_2 \rightarrow$ Trip (8) only
For $F_3 \rightarrow$ Trip (9) only
X = Switchgear

1 = Mains
2 = Bus bar for non essential loads
3 = Bus bar for essential loads
4 = Bus coupler

Fig. 43.9. Scheme of mains supply and inplant auxiliary supply for industrial plant.

During a fault (F_2) in generating plant, breaker (8) should trip and (7) should remain closed.

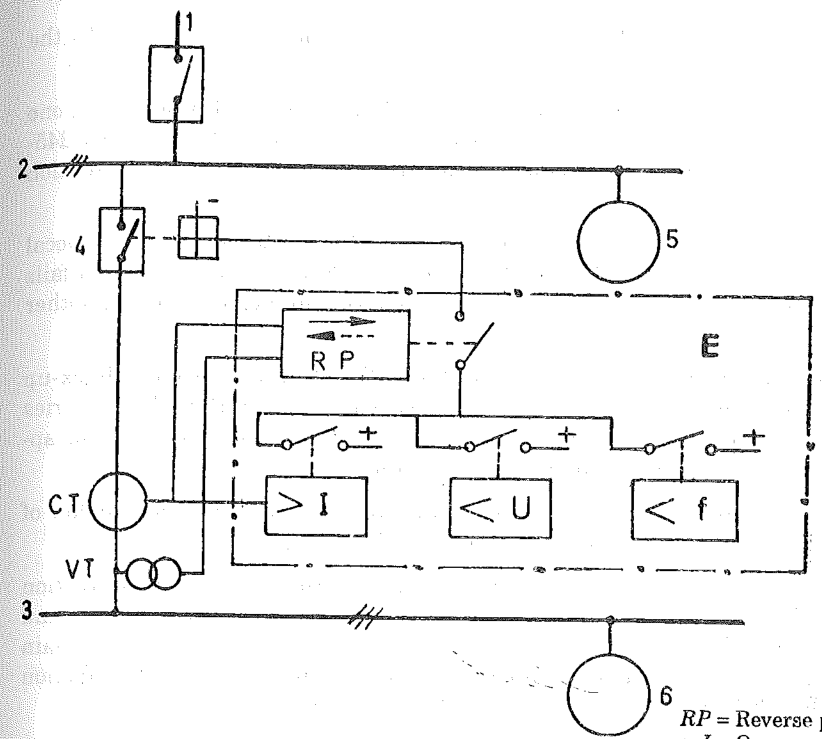
During a short-circuit within the plant (F_3) only faulty part is disconnected without interrupting the mains supply or generator supply.

A protection scheme for quick disconnection of mains supply in the event of fault (F_1) is described here.

Non-essential loads are connected to busbar 2 and essential loads to 3.

The following conditions must be satisfied by the installation:

— Busbar system must be equipped with switchgear and protection for quick disconnection of mains supply which responds to critical conditions in the plant and trips buscoupler.



RP = Reverse power element
> *I* = Overcurrent element
< *U* = Undervoltage element, connected to VT
< *f* = Under-frequency element, connected to VT
All elements in single relay unit *E*.

Fig. 43.10. Protection scheme for system disconnection for Fig. 43.9 symbols as in Fig. 43.9.

— Enough power should be available from generator *G* when mains supply is disconnected.

— Enough power should be available from mains, when generator *G* is disconnected.

The protection scheme has several relays, the main component being a directional power (*RP*). It is a highly sensitive static relay.

The directional power relay *RP receives input reference voltage from VT via* rectifier bridge and input current from CT *via* another rectifier bridge. The measuring angle of the relay is 60°. This angle gives the best results for short-circuit conditions considering the d.c. component.

The phase angle between rectified outputs of current and voltage are made in positive and negative half waves which makes the measurement very rapid and reliable. Two phase comparison is made per cycle. At 50 Hz the maximum resolution of reed relay contacts is 10 to 15 ms.

The protection also incorporates overcurrents element $>I$, under-voltage element $<U$ and under-frequency element $<f$. *These elements are housed in a single relay (E).*

Section III. BACK-UP PROTECTION, CENTRALLY CO-ORDINATED BACK-UP AND PROTECTION SIGNALLING

43.10. BREAKER BACK-UP LOCAL BACK-UP

The breaker back-up and centrally co-ordinated back-up will be described further in this section.

Breaker back-up protection is employed in installations, where the failure to interrupt a short-circuit, due to breaker failure, could cause serious damage or disturb the stability of the network. Back-up protection provides a safeguard against failure of primary protection. *In breaker back-up* *protection* if faults is not cleared by the circuit-breaker or primary protection, it will cleared by the additional back-up circuit-breaker provided in the same station.

In EHV systems it is now a common practice to provide two different types of protections, one main and other back-up. The cost of EHV circuit-breakers being very high (Rs. 5-15 lakhs per 245-400 kV breaker), it is generally uneconomical to provide a duplicate breaker. Hence more attention is paid to protection scheme.

The protection scheme (generally provided in conjunction with busbar protection) based on local back-up protection, provided with features such that if the circuit-breaker of main protection fails to clear, the protection scheme senses the breaker failure and sends tripping command to another adjacent circuit breaker.

The protection scheme comprises primary protection element, (*A*) and additional back-up protection element (*B*) and complex logic system (Refer Fig. 43.11). The choice of the scheme varies with every application. Accordingly, the wiring of the relay is made for specific application or appropriate relay elements are plugged in to form the complete system.

If both the breakers in the station (for primary and back-up) fails to operate, then breaker of remote back-up provided in other stations may operate and clear the fault.

The breaker back-up protection scheme is generally provided with the bus-bar protection scheme. The principle of protection is that the command is given to the main circuit-breaker and a time lag relay for check. The time lag check relays checks whether the circuit-breaker of main protection has interrupted the current in a period of about 50 to 100 ms. (Time of primary protection say 20 ms to 40 ms and total break-time of circuit breaker 40 to 60 ms.)

If primary protection has been successful (as can be sensed by sensing current through circuit-breaker and CT primary) the back-up breaker does not get tripping command from breaker-back up protection relay. In case the main protection circuit-breaker has failed to interrupt (current has continued to flow), the breaker-back protection sends tripping command (after 50 to 100 ms) to back-up breaker.

The breaker back-up protection scheme with bus-bar system comprise the following items per breaker : (incorporated in block *B* in Fig. 43.11).

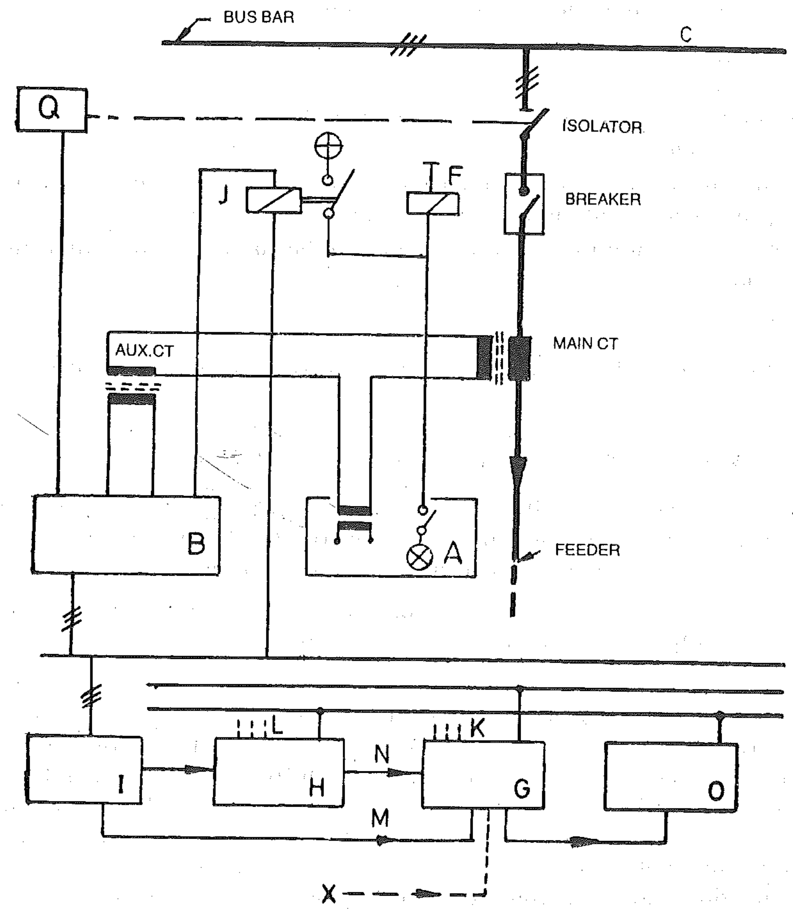
— 3 high speed single-phase current relay elements.
— 1 or more starting elements.
— 1 or more time lag elements.
— 1 or 2 tripping relays.

These elements are suitably arranged to form a complete back-up protection scheme. Logic relations decide as to which circuit-breaker should be tripped. These logic circuit derive inputs from auxiliary CT's in series with the circuit-breaker of primary protection.

Ref. Fig. 43.11 Block *B* contains three adjustable over-currents relays, starting relays for each phase and all three phases, two adjustable timing elements, two outputs for energing the tripping relays. The protective system also contains facility for signalling, monitoring units, intermediate CT, input filters for starting relays and tripping relays besides the main blocks illustrated in the figure.

43.11. USE OF MICRO PROCESSOR FOR LOCAL BACK-UP

It is now a common practice to have two forms of primary protection for transmission lines working on different principles (*e.g.* distance and over-current). It is assumed that at least one protection system will operate on occurrence of a fault. The cost of high voltage circuit-breakers being very high, it may not be economical to duplicate the high voltage circuit breaker even though higher reliability can be achieved by back-up breaker. More attention is being paid to the provision



A = Primary protection element, one for each feeder
B = Breaker back-up protection element, one for each feeder
C = Busbars
D = Tripping line Allocated busbars
E = Blocking or release line
F = Breaker trip coil
G = Logic for release
H = Monitoring module (with fault location facility)
I = Tripping line monitor
J = Tripping contactor
K = Connection between starting contactor and *G*
L = Monitoring connections between each module and *H*
M = Logic connection between *I* and *G*
N = Blocking connection
O = Signal module (output unit for internal and external signal)
P = Signal line
Q = Isolator replica generates logic signals at electronic level, which correspond to position of isolators.

Fig. 43.11. Schematic diagram of static breaker back-up protection scheme.
(*Courtesy* : Brown Boveri, Switzerland).

in protection scheme which will operate and clear the fault by tripping the *adjacent breaker* in case of failure of the breaker main protection to trip.

The fault detector devices in the protection scheme are normally simple instantaneous over-current relays but complex logic circuits are associated with these to ensure that correct breakers are tripped under all system operating conditions and provide the necessary security against wrong tripping.

Microprocessors or minicomputers (Ref. Ch. 43-C) are used to advantage for this function to replace the present hard wire logic system. The minicomputer is loaded with a program which takes into consideration various system requirements.

The advantages of programmable processors are the following :

— considerable saving in relay panel space.
— reduction in panel wiring at site.
— reduction in number of multi-core required between plant items and the control room.
— greater ease to change logic to current initial mistakes or to suit subsequent system changes.
— reduction in amount of information which has to be transferred from one department to another during the design and manufacturing stages of logic system
— reduction in overall cost due to reduction in the number of stages and thus time required to provide working system.

Remote Back-up Protection

The remote back-up refers to back-up protection given by protection system in the adjacent station.

43.12. COMPUTER BASED CENTRALLY COORDINATED BACK-UP

Opening of a back-up breaker generally causes loss of power to a larger area and also system disturbance. In centrally co-ordinated back-up protection, the Grid Control Centre (Ref. Ch. 46) receives information from various sub-stations that a fault has not been cleared.

The computer aided control centre takes into account the system conditions at the time of fault land decides which back-up breakers should be opened to clear the fault with minimum system disturbance.

In order to achieve correct back-up breaker operation, it is necessary to transmit a large amount of data from and to individual sub-station if all the analysis of the fault conditions is to be done by the central computer. This would be too complex and prohibitively costly. Instead of sending all the information (Ref. Sec. 46.5) the data which can be processed locally in the sub-station is processed (by the micro-processor based mini-computer) in the sub-station itself and only essential information (data) is telemetered (transmitted to a remote) Grid Control Centre. This information (data) is compared with data received from other sub-station and the program is such that the decision as to which back circuit-breakers should be tripped is taken by computer based Grid Control Centre. This decision is then conveyed to respective sub-station in the form of coded telemetric signal. On receiving these instructions the appropriate back-up breakers are opened. The sequence of tripping of back-up breakers is in accordance with a pre-arranged program.

Smaller mini-computer with their micro-processor (central processing units) is used in individual sub-stations to determine which part of the sub-stations is faulty. The back-up protection scheme (B) in that station (generally incorporated in the busbar protection scheme) has a provision to determine as to which feeder is faulty and to send signal that a particular breaker has not cleared the fault though main protection (A) had instructed that breaker to open. These signals are processed by the mini-computer in that sub-station and relevant data is transmitted to Grid Control Centre. The grid control centre determines which adjacent circuits should be disconnected to clear the fault with least overall disturbance to the system, and also which circuits should be blocked (negative tripping) in order to maintain system stability).

43.13. PROGRAMMABLE EQUIPMENT FOR PROTECTIVE RELAYING MEASURE MENTS AND CONTROL (PPRMC)

In *Hard-Wired electromechanical or static relays* described earlier, the components of the protection system are physically interconnected and are usually for specific purpose (*i.e.* over-current relay protects against over-current and is wired according to its scheme). Hardwire logic is essentially unalterable. Hard-wired relay is set for certain pick-up condition and has certain specific characteristic.

The present trend in power system protection, measurement and control is to use *Programmable* equipment instead of *Hard-wired* equipment. The use of programmable equipment incorporating micro-processor and static digital/analog devices reduces the complexity of the entire protection scheme.

The protection scheme has to perform several complex functions. This includes

— to sense abnormal condition/fault.
— to decide whether to give an alarm or trip command.
— to decide which main circuit-breakers (primary or main protection) should be tripped.
— to decide whether to trip back-up breakers or not ? Which back-up breakers can be tripped with least disturbance ?
— in which sequence Autoreclosure should be carried out ?
— whether breaker should be reclosed or not ?
— how much abnormal condition (say power swings) are permissible that breaker should not trip ?
— what are the conditions at remote station bus ?
— whether remote breakers should be tripped or blocked ?
— what is a sequence of switching in the network ?
— synchronising checks before reclosing ?
— *Monitoring* : checking at periodic intervals, the auxiliary circuits, relay-breaker-CT-VT and other devices to check their operational readiness and health.
— Required fault clearing time of main and back-up breakers.

These complex and multifarious functions are possible with programmable protection schemes in conjunction with static relays and digital logic circuits.

The variables in main primary circuit (current, voltage, power factor, frequency) are given to measurement/protection/control scheme *via* CT/VT/tranducers. Some signals are converted to Digital form in Analogue to Digital converters (A/D)

The entire system has at its centre a large scale integrated circuit (LSI) microprocessor. The microprocessor processes the information by means of built-in static logic circuits, memory and other modules.

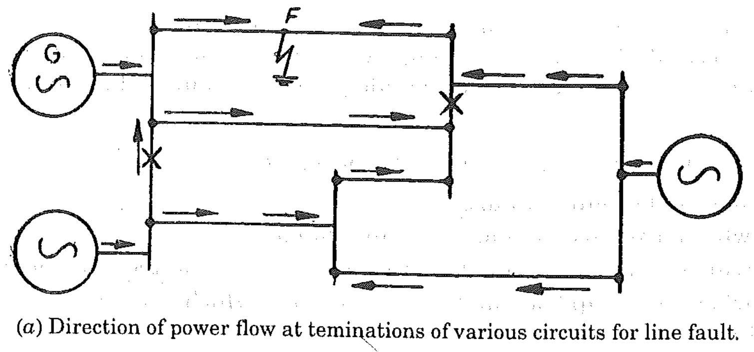
The processing is performed by means of *programmable* microcomputer. The *programmes* are prepared to cater for specific application. These programmes can be prepared to suit local system conditions.

43.14. PRINCIPLE OF CENTRALIZED BACK-UP PROTECTION (CBP)

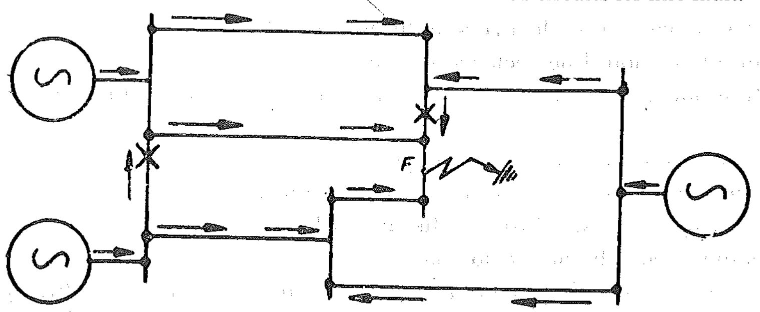
A real-time on-line computer system is necessary for centralized computer aided back-up protection and post-fault control the basic approach is to substitute logic for measurement.

The faulty circuit in power system is distinguished from healthy circuit by the fact that fault circuit alone has an inflow of fault power at one or more terminations and no out-flow at any termination (Ref. Fig. 43.12).

The central computer is supplied with the data on the directions of (fault) power flow from all circuit-terminations. The computer programme is such that it can determine the faulty circuit by very fast able look-up and then decide which back-up circuit-breakers should be tripped for back-up clearance if one or more of the circuit-breakers of primary (main) protection fail to clear the fault condition within desired time.



(a) Direction of power flow at teminations of various circuits for line fault.



(b) Direction of power flow at terminations of various circuits for busbar fault.

Fig. 43.12. Explaining CBP.

Note. During a fault in a circuit the direction of power flow at the terminations of that circuit is towards the fault F.

Generally, back-up clearance will involve tripping of a section of busbar as only one circuit breaker is provided per feeder for economic reasons. The central computer will then wait for the total break-time of the slowest circuit-breaker in the system plus a suitable safety margin, to service the circuit-breaker trip signals (signal that the circuit-breaker has tripped and cleared the fault). If all such signals arrive, the back-up protection programme will stop; if one or more such signals do not arrive, appropriate trip command will be issued to the relevant out-station.

The trip-command (if any) from central control will be checked for compatibility with the local situation as seen by the out-station before the tripping of back-up circuit-breaker is initiated. The purpose of this check is to prevent false tripping of back-up breaker due to false command from central back-up control station (Grid Control Centre). Generally, outstation can determine/only check whether the particular circuit *may be faulty* or *is faulty* ; and not that *it is faulty*. The last function is determined by central back-up protection. (Protection in outstation might have failed and cannot be relied upon for back-up).

The central computer tables must be continually updated with any change in circuit configuration. Thus the outstation must inform central computer of any circuit-breaker of isolated change of status as a low priority interrupt.

43.15. POST-FAULTY CONTROL (PFC) BY DIGITAL COMPUTERS

Post fault control is necessary after opening of main and back-up circuit-breaker to keep the power system in satisfactory operating condition. Possible actions to be taken include

— load shedding

— generation readjustment

— switching-in of available standby feeders of transformers

— system islanding (splitting)

Central computer can examine several possible post fault conditions before the breaker clears the fault and determines what action may be required to keep system stability with minimum outage. The actions must be pre-programmed on the basis of recent analysis of the system.

The central computer is pre-programmed with tables of specific loads to be shed or switches to be opened corresponding to specific generation/load inbalances. For other aspects, a periodic system security assessment programme is simulates successively all possible contingencies and checks overloads and stability limits, which is pre-assessed off-line. This programme is run periodically or whenever a significant load change occurs, or whenever there is a change in power system configuration. A pre-requisite for this function is that, additionally to the information required by the back-up protection programme, the central computer needs information on busbar voltages, generation levels, circuits watts/VARs flow, etc. These data are scanned at regular intervals (second/minutes) by an existing data loggers and elementary system.

43.16. COMMUNICATION LINKS FOR PROTECTION SIGNALLING

The communication links for protection signalling between out-station and central control station can be one of the following types :

— Pilot wires specially for protection/communication signalling

— Telephone wires

— High frequency carrier channel

— Radio/Microwave channels of very high ultra high frequencies.

— Satellite communication

The communication channel between out-station and central control forms a part of back-up protection scheme.

Digital Message System

Signals are physical representation of a message, and therefore carries the information to be processed. The *Binary signals* can assume only two values either '0' or '1', the '0' value represents not present and '1' value represents present. The logic operations AND, NAND, NOR OR, and the combinations thereof manipulate logic functions in form of binary language of '0' , '1'. A change of signal state of a binary device represents in its message content elementary decision between two possible values 0, 1. In technical terminology, it contain the 'unitbit' called binary digit.

When a varying analogue quantity is to be converted into digital message, it should be converted into digital form in A/D conversion device.

A code is the assignment between individual values of the quantity and the signal states of several binary positions by means of which these values are to be digitally represented.

The analogue circuit quantities or messages are converted into digital messages. These digital messages are in form of 0-1 pulses having certain code. The frequency of signals may be voice frequency or high radio frequency.

43.17. FIBRE OPTIC DATA TRANSMISSION

This technique is being used for machine-tool control or plant process control and power system protection.

The conventional electronic signals are communicated through shielded copper wires of good conductivity. The electrical noise, electromagnetic field disturbances tend to disturb the signals. One method of overcoming this problem is to employ fibre-optic cable for transmitting the control signals fibre-optic cable consists of specially developed glass cable. The light signals can be transmitted through such cable very efficiently and the effect of electrical noise on transmission is completely eliminated.

The transmitter at sending end converts the electrical pulses into light pulses. These light pulses are transmitted through the FO cable. At the receiving end the light signals are converted into electrical signals.

At present silica clad silica optical cables have been developed for working lengths of 40 km before repeaters are necessary. They can handle data rates in excess of 100 M bit/sec.

Development of optical sensors and integrated optics has made a major impact on protection signalling in early 1980's.

Experimental optical link current transformers have been developed the scheme incorporates auxiliary CT's mounted on hollow insulator. The output of auxiliary CT's is given to pulse frequency modulated transmitter. Optoelectric techniques are used for controlling HVDC thyristor valves.

The transmitter drives a gellium-arsenide light emitting diode (LED). Light pulses from the diodes are transmitted through fibre-optical cable to relay room. In this room the light signals received from FO cable are converted into electrical pulses by receivers. The electrical signals are supplied to static relays. Thus the optical system forms a link between outdoor CT and indoor static relay.

43.18. LOCAL BREAKER BACK-UP PROTECTION : BREAKER FAIL PROTECTION ; STUCK-BREAKER PROTECTION

This form of protection has other titles like *Local Breaker Backup Protection, Breaker Fail Protection ; Back-up Tripping Protection.* If a circuit breaker fails to open or clear the fault; the back-up breaker should be operated either 'locally' or 'remote'. The local back-up breaker operates in the same sub-station. The method of achieving local breaker back-up operation is called 'Breaker Fall Protection' of 'Breaker Stuck protection' or 'Back-up Tripping Protection'.

Basic Scheme of Breaker Fall protection is illustrated in Fig. 43.13. As the main protection operates; the breaker fall protection is also initiated. If the main breaker falls to clear the fault, a time delay relay is arranged to operate the required back up breakers so as to clear the fault. The total time required for fault clearance by the back-up breakers depends mainly on the setting of the time delay relay.

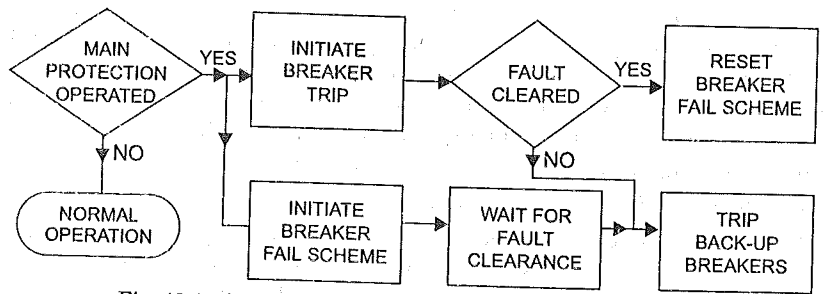


Fig. 43.13. Basic flow diagram of local back-up protection.
Courtesy : GEC measurements, U.K.

Fig. 43.14 illustrates the total time required for clearance by back-up breaker.

Refer Fig. 43.14. The setting of time delay relay in the breaker fail scheme must be longer than the total break time (Circuit breaker time) of the main protection breaker plus reset time of the fault detector relay so that back-up breakers do not operate if the fault detector relay has already reset (*i.e.* the main circuit-breaker has successfully cleared the fault).

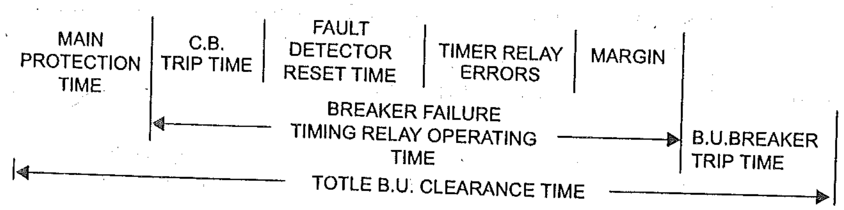


Fig. 43.14. Time components in local breaker back-up.
Courtesy : GEC measurements U.K.

Whether the main breaker has cleared the fault or not is detected by 'an instantaneous over current relay followed by a definite time relay' which together find out whether the main current is still flowing after the tripping signal to trip coils of main circuit-breaker of the faulty feeder.

43.19. UNINTERRUPTED POWER SUPPLY (UPS)

Complex, critical electrical and electronic systems need uninterrupted power supply. Examples of such critical loads include process computers; process control instruments, communication links, relay, boiler flame supply, boiler control, furnace supply, protection circuits, critical alarms etc. For some loads, voltage dips/frequency variations are not allowed. UPS systems provide uninterrupted a.c. power supply to such critical applications.

There are two types of UPS

(*A*) UPS with some delay of several cycles.

(*B*) UPS with time delay less than a fraction of a cycle.

In type *A* above, for a time delay of 4 to 8 cycles, mechanical switches can be used for transferring supply from main to the stand-by generating source.

In type *B* above, there should not be any delay or interruption; hence a continuous or float type UPS system have been illustrated in Figs. 43.15 and 43.16.

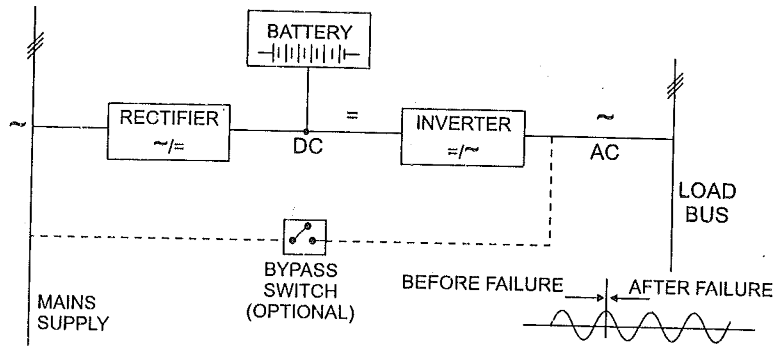


Fig. 43.15. Un-Interruption Power Supply (UPS).

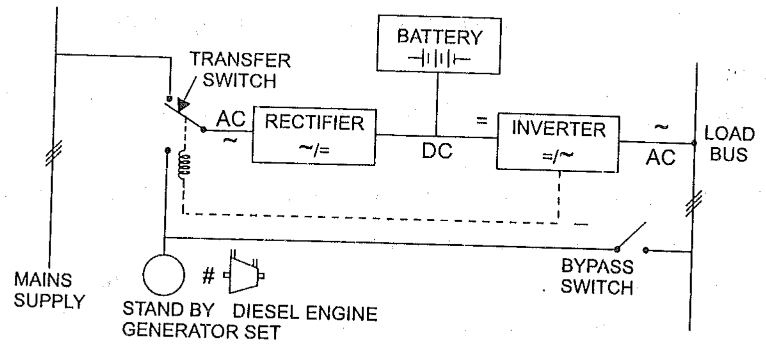


Fig. 43.16. A typical high power UPS with standby generator set.

A solid state UPS is basically composed of the following :

(*a*) Solid State rectifier battery charger.

(*b*) D.C. Storage Battery.

(*c*) Solid State inverter.

(*d*) Solid State (Static) Switch (Optional)

During the normal operation, the a.c. input feeds the rectifier. The rectifier converts a.c. into d.c. and charges the battery. Simultaneously, the rectified supply is inverted to a.c. by the inverter.

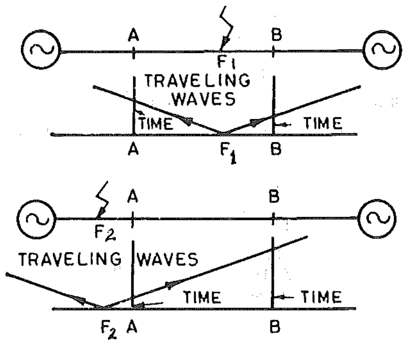
When a.c. supply fails, the battery supply provides the alternative power to the inverter and the continuous uninterrupted a.c. supply is available on the a.c. load side. For a time of 10 to 60 minutes battery can be arranged. For longer power supply duration or for higher capacity standby supply; diesel generator sets or gas-turbine driven generator sets are used. These are brought into circuit automatically when main supply fails.

43.20. DIRECTIONAL WAVE RELAYS FOR FAULT DETECTION AND PROTECTION OF OVERHEAD LINES

The Directional Wave Relays are ultra-fast (2-5 ms) and have been developed during 1980's for protection of overhead lines of any length against phase to phase faults and phase to ground faults. Directional wave relays are also used in conjunction with distance relays for line protection.

The Directional wave relay (DWR) uses the *directional wave detection principle* which detects the direction from which the travelling waves originate. If the point of origin is external to the protected line section the protection blocks and if internal, the protection provides a high speed tripping output which is phase selective.

This principle is illustrated in Fig. 43.17 in terms of the direction of motion of travelling waves generated by a change in the electrical state of the network (*i.e.* fault breaker operation etc.)



F_1 Internal fault for section *AA* F_2 External fault for section *BB*

Fig. 43.17. Principle of Directional Wave Relay (DWR).

Consider protection section A.B.

For internal Fault F_1 the direction of travelling waves originating in F_1 will be F_1A and F_1B.

The external fault (F_2) the direction of travelling waves will be F_2A and F_2B.

The direction of wave at Point A has reversed.

At point *B*, the time taken by the wave F_2B is mush lesser than that taken by wave F_2B.

The Directional Wave Relay senses the following :

1. **Direction of Wave** with respect to the protected section relay location.

2. **Amplitude of the Wave** with respect to setting.

In DWR the steady state currents and voltage are suppressed in active and passive filters and only sudden changes are detected. The direction to the fault is established by determining the relative polarity of the sudden changes in voltage ΔU and current ΔI. For external conditions these have the same polarity and for internal conditions the opposite polarity. The directional decision is made in the first 2 to 5 ms after fault incidence and all subsequent information is ignored.

The DWR has two modes of operation.

1. The independent mode determines whether the fault is internal or external by direction and level setting. It is independent of the communication channel and provides ultra high-speed tripping for nearby faults.

2. The more sensitive dependent mode requires information from the remote terminal to establish whether the fault is internal or external in the usual manner of directional comparison and carrier acceleration principles used in distance protection schemes.

In Fig. 43.17, for fault F_1, the DWR at A will detect the internal fault in independent mode and will take tripping decision within 2 to 5 ms. For fault F_2 the DWR at A will remain inoperative, and the DWR at remote terminal B will depend on the carrier acceleration or carrier blocking signal from terminal A. For a fault F_2 very near terminal 'A' the DWR at B cannot precisely determine whether the fault is internal or external. Hence it has to take help of the usual techniques used in carried aided distance protection of long lines. By such combination of the two modes the DWR along with carrier aided distance protection scheme provides fast and selective protection of 100% length of overhead transmission line.

The DWR relay incorporated in Distance protection scheme uses both steady state (50 Hz waves) and transient variations (within milliseconds) but the setting are based on 50 Hz quantities.

Testing : The Directional Wave Relays can be tested by means of special test kit for Dynamic Testing. The tests can be performed on DWR and Distance Protection Scheme.

QUESTIONS

1. Explain the causes of electrical noise in static relays and necessary precautions in installation to eliminate the same.
2. Write short notes on —
   — shielding and earthing
   — uninterrupted power supply (UPS)
   — fibre optical link for data transmission
   — overvoltages in static relays
   — noise in static relays
3. State the merits of static motor protection. Describe a typical static motor protection scheme with the help of a heat block diagram. Describe function of each functional block.
4. Describe principle of a static bus protection based on directional comparison principle.
5. Explain the need for back-protection. Explain principle of breaker back-up protection scheme.
6. Explain the role of centrally co-ordinated breaker back-up in a large power system. Describe the scheme of centrally co-ordinated breaker back-up employing a digital computer.
7. Explain the need of post fault control from central control station. What are the main functions of the post fault control.

43-B

Digital Relays, Microprocessors Based Relays, Fault Recorders and Fault Locators

Three levels : Control centre, Substation, Unit. Functions at each level — Components of Digital Relay, Components of Microprocessor based relays.
Part I Digital Relays. Block diagram — functions of each block — basic processes in Digital Data Processing — Binary system, Word, bits, components.
Part II — Microprocessor based Relay.
Block diagram — functions — Microprocessor — Microcomputer — Functional parts, Architecture, Block diagram or a Distance Relay.
Chapter 43-C — Microprocessor Based Substation Control and Protection

43.21. ENTER MICROPROCESSORS IN PROTECTION TECHNOLOGY

Power Engineers need understanding of basic principles and applications of microprocessor based protection control system in addition to the conventional protection systems.

The microprocessor based protection and control at following hierarchical levels (Fig. 43.18).

Control centre level	: Load Control Centre
Substation Level/ Plant Level	: Control rooms of Substation, Generating Station, Load Centres.
Unit Level	: Individual 'Units' in the substation/ generating station/Load centres *e.g.* transformer, busbar, motor transmission line.

These levels are linked by Power Line Carrier Communication channels (PLCC)* and microwave communication channel. The data flows from unit level to upper levels and from upper levels to unit levels *via* the Data Bus. Each level has certain protective, Supervisory/monitoring and control functions.

Before 1980's the protective functions were independent of control and monitoring functions. Monitoring Functions and Control Functions were performed by different systems. The functions of protective relays was limited to sensing the fault/abnormal operating condition and arrange tripping of circuit breaker under main protection and if necessary back-up breakers. The automatic control included Synchronising checks, auto reclosing duty etc.

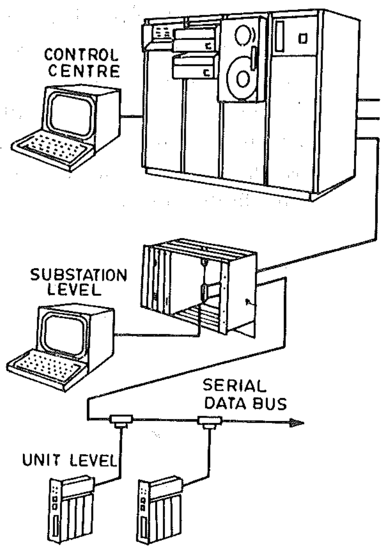


Fig. 43.18. Three levels in microprocessor based Protection, Control Monitoring (PCM) system.
Courtesy : ASEA, Sweden.

* Refer Sec. 46.9 Terms and Definitions.

Digital protective relays, monitoring and control devices in these three levels are in communication by means of power line carrier communication channels (PLCC). (1980-1990)

Changing Scene

With the availability of microprocessor based relays, digital techniques, data transmission facilities microcomputer etc. the functions of supervision, control and protection can be made complementary rather than independent. Functional modules can be incorporated in Combined Protection Control and Monitoring System (CPCM).

In the modular concept of protective and control systems, the required modules are plugged-in to form the desired protection cum control system. The individual level (*e.g.* unit level) has an interface with the next level (*e.g.* substation level) and also has man machine interface. The telecommunication system is used between different hierarchical levels.

This chapter describes the basic components of Digital Relays and Microprocessor based Relays. The Combined Protection Control and Monitoring and Control Systems (CPCM).

PART I
DIGITAL RELAYS

43.22. BLOCK DIAGRAM AND COMPONENTS OF A DIGITAL RELAY *

There are two families of digital relays.

1. Hardwired digital relays incorporating A/D convertors and Digital processing circuits.
2. Programmable digit relays incorporating microprocessors or minicomputer.

Basic components and processes involved in a digital protective relay are illustrated in Block Diagram Fig. 43.19 (*a*) described here as an example.

The three phase AC inputs derived from CTs and VTs are fed to Block 2. Block 2 comprises analog processing compensating circuits. In this block, the measured currents and voltages are developed into a set of quantities required for measurement processing and operation of the relay.

In Block 4 A/D Conversion the phase informations contained in these quantities are converted from the analog signals to representative square wave digital signals.

The equivalent digital signals from Block 4 are fed Block 7 for *digital processing. Block 7 consists of phase comparators, logic gates and other digital circuits required for signal processing. Block 7 also receives other external digital signals from Block 3. These include external data regarding back up breaker and other circuits which have an interface with the protective relay.*

The digital processing carried out in Block 7 is controlled by current and voltage supervision functions carried out in Block 5. *In Microprocessor Based Relays functions of Block 7 and Block 5 are performed by a Microprocessor.*

Block 8 provides an interface between the relay and the circuit-breaker trip coils Block 9 gives indication display on the front face of the relay and is called Man-Machine Interface. In the event of power system disturbance, for which the relay reacts, the events are displayed on Block 9. Signalling contacts enable communication with the peripheral devices like sequence of event recorders, reclosing relays etc. With digital relays there is a provision of fault recorder, fault locator etc.

Block 1 (D.C./D.C. convertor) provides a galvanic separation between the station auxiliary DC system and the protective relay. The time lag relays in Block 6 determine the operating time of the back-up function of the relay and are therefore linked with the Block 7.

Referring to Fig. 43.19 the functions and description of electronic components in a digital relay are summarised in Table 43.2.

[In microprocessor based relay Blocks 7 and 5 are within a microprocessor of the relay]

* The Blocks in Digital Relays, Microprocessor based relays have similarity.

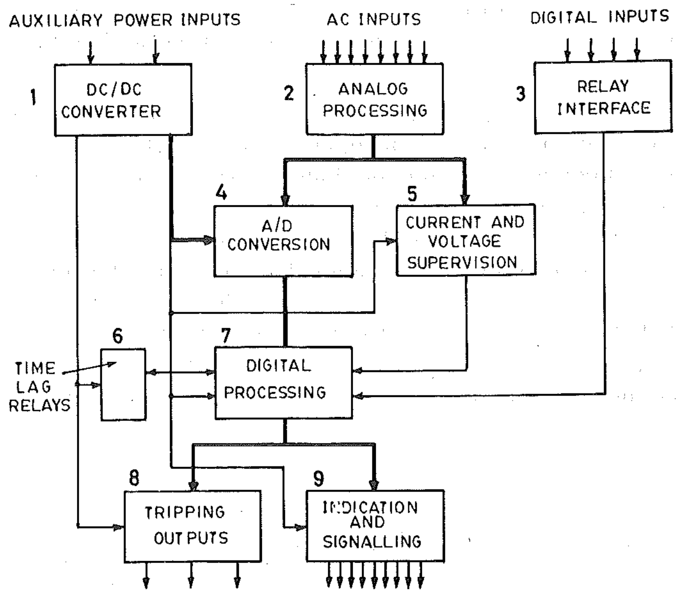


Fig. 43.19. Block diagram of a digital relay.
Courtesy : ASEA, Sweden.

Table 43.2
Summary of Components in a digital protective relays

Block in Fig. 43.19	*Functions*	*Description*
1. D.C./D.C. convertor	Galvanic separation between Auxiliary D.C. supply (Station battery system) and the static relay.	
2. Analog processing, compensating and setting circuits.	3 phase AC inputs include Secondary current of CT, Secondary voltage of VT.	Include different processes required for relay measurement *e.g.* — Amplitude comparison — Zero crossing detection — Phase comparison in sequential logic circuit. — Measurements *e.g.* current or voltage or impedance or direction. — Supervision and control functions by amplitude comparators. — Filtering.
3. Relay Interface with external Digital Signals	To receive external digital inputs and feed to the digital processing block 7.	External digital inputs may include signals from remote terminal, signals regarding back-up protection etc.
7 A/D converter	To convertor analog signals into digital square wave signals	These signals are subsequently fed to the digital processing block 7.
5. Current and voltage supervision	To control digital processes in block 7.	May be included in Block 7 in a Microprocessor.
6. Time-lag relay block.	To determine operating time of back-up relays through block 7.	
7. Digital processing block	To process the digital signals received from A/D converter (4) and the Digital Input interface (3) as per required relay logic.	Comprises — Logic circuits for relay operation. — Multiplexers — Encoders, decoders — Memory circuits and other digital electronic circuits.
8. Tripping output.	The trip-command to circuit breakers is given by this block.	The tripping output is generally fed to appropriate auxiliary relay.
9. Indication and signalling	To indicate whether the relay has operated. To provide signals to remote terminals.	In addition, the functions may include display Disturbance recording, Fault recording etc.

43.23. BASIC PRINCIPLES OF DIGITAL RELAYS

Ref. Fig. 43.19. The protective relays receive analog inputs from the CT's and VT's connected in the protected circuit (Block 2). These analog signals are processed in Analog processing unit (Block 2). *The processed analog signals are fed to the analog to digital convertor (A/D converter) (Block 4).*

Digital Signals

Analog signals have continuous faithful wave forms *e.g.* Secondary voltage of a VT, secondary current of a CT.

Digital signals are in form of coded square pulses which represent discrete elements of information (data). In digital system, the signals are in 'binary' form *i.e.* only two discrete values referred to as binary coefficients 0 and 1 or logical values true and false.

The number of binary digits needed to *encode* the various discrete elements of information (data) has a significant influence on the design of a digital system.

The digital system generally operate on groups of 8 or 16 or 32 bits of information atonce. The range of the digital system of encoding the information by a n bit group is 2^n. Hence digital systems with larger bit operating group can process a wider range of concoded information.

The earlier digital relays used microprocessors of 8 bit groups. **Some recent digital relays are with 16 bit microprocessor.**

Representation of Digital Information.

The information to be processed may be :

— Textual *e.g.* status of a plant *viz* normal or emergency.
— Numerical *e.g.* value of current, voltage, power etc.
— Logical *e.g.* logical conditions imposed on a relay to operate.

The information usually takes from a sequence of alphabetic characters, punctuating symbols, decimal digits and symbols representing arithmetic operations, logical values and logical operators. The information also includes the spaces which mark the boundaries between various words or quantities.

This form of information is represented in a digital system by codes of binary digits. Since the information must be fed into the input unit, processed in the processor unit and given out by output unit in coded form, there should be possibility of 'encoding' and 'decoding'. Each element of information must have unique representation.

Binary Number System.

Binary digit can take two values (0 or 1) corresponding to ('open' or 'close') and is said to be base 2. Binary numbers are formed by successive powers of binary base. Whole numbers and fractions can be formed by using binary system. For example a decimal number 86 is represented by a binary number 1 0 1 0 110 as follows :

1		0		1		0		1		1		0,	
1×2^6	+	1×2^5	+	1×2^4	+	0×2^3	+	0×2^2	+	1×2^1	+	0×2^0	= 86
645	+	0	+	16	+	0	+	4	+	2	+	0	= 86

To represent 86, binary series requires seven positions, but only two digits 0, 1. The valancy of individual binary position of dual number is obtained by falling powers of base 2.

A Binary number (1 0 1 0 1 1 0)

B 'A' as a relay combination,

1 = close 0 = Open

C 'A' as an amount of binary counter

This can be represented by modern hardware by relay combination and binary counter is shown in Fig. 43.20. The number 86 is represented by binary code (A) by (B) and (C).

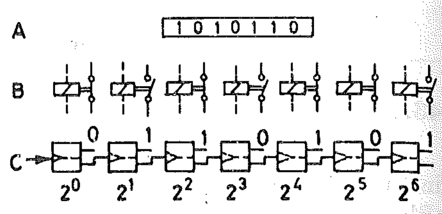


Fig. 43.20. Dial (Binary) number system.

Conversion binary to decimal and vice versa

Simplest method consists of repeated halving of decimal number. Each halving produces a new dual digit which is equal to the remainder which can be 0 or 1 (even or odd number)

Example Conversion Decimal to Binary

Example : 56 →111000

56 : 2 = 28 remainder 0
28 : 2 = 14 remainder 0
14 : 2 = 7 remainder 0 ↑Dual number 111000
7 : 2 = 3 remainder 1
3 : 2 = 1 remainder 1
1 : 2 = 0 remainder 1

Dual number is converted in decimal number by taking highest binary digit and doubling it, adding to second highest binary digit to the result, doubling it again, adding to this the third highest binary digit and so on.

Example : Binary to digital conversion

1 1 1 0 0 0 =

1 × 2	+ 1	= 3
3 × 2	+ 1	= 7
7 × 2	+ 0	= 14
14 × 2	+ 0	= 28
28 × 2	+ 0	= 56
		RESULT

Processing Binary Information

Each element of information within digital protection and control system is represented as a binary code and is stored, transmitted, processed as a set of binary signals '0' - '1' series. Within the digital circuits, the binary signals are processed by digital logic circuits which route the binary signals through appropriate combination of logic gates. Each logic gate implements primitive binary logic which is described mathematically by Boolean Algebra Logic corresponds directly between logical operators and the digital logic gates. Gives principles of Logic circuits. Described logic functions and their applications to digital protective relays.

Boolean Algebra provides a method and a set of rules for logic operations. Basic logic operations NOT, AND, OR and their combinations NAND, NOR etc. are used as building blocks *for forming systematic logic circuits. By using Boolean algebra the logical circuits are manipulated and designed, simplified with mathematical accuracy.*

The logic circuits is formed on the basis of rules from Boolean Algebra and mathematical simplification.

Combination Logic

Digital protective systems have built-in-digital signal processing circuits. The analog inputs are received from secondaries of CT, VTs. Digital signal inputs are received from RTU (Remote Terminals Units) and from other contacts.

Other textual signals are received from the man-machine interface. These data are either in textual numerical or logical. Each discrete information is first converted into digital form to equivalent code in terms of '0' and 1.

In static relays, the *digital signal processing system (Block 7 to Fig. 43.19) is required to produce output signals which are fed to tripping outputs (Block 8) and indication, display signalling unit (Block 9). The signal processing involves logical combinations of input signals. The combination logic functions (Boolean Functions) are implemented using network logic gates in which the signal paths do not form feedback loops. The absence of feed back loops ensures that the output of logic circuit is determined only by logic function of the circuit is determined only by logic function of the circuit and the present set of inputs.* Such a circuit is called 'Combinational logic circuits'.

Combinational logic is used extensively in digital protective relays as illustrated in Fig. 43.19, Static Busbar Protection, Static Distance Protection. It provides many of the logical and arithmetic functions used in digital signal processing and computing systems.

Truth Table

The function of Combinational logic circuits in protective relays can be specified as a Boolean Equation in which the output variable is expressed as a function of input variable. This equation defines the value of output for each combination of input variables. The complete set of inputs and their corresponding output are generally represented in the truth table.

Arithmetic Operations

Arithmetic operations of fundamental nature are performed in

— digital processing systems (Block 7, Fig. 43.19)

— Arithmetic Logic Unit (ALU) within the central processing unit (CPU) of a computer or a microprocessor.

Combination of logic gates can be used to implement arithmetic operations on binary numbers.

Arithmetic addition is the most fundamental operation in binary digital system.

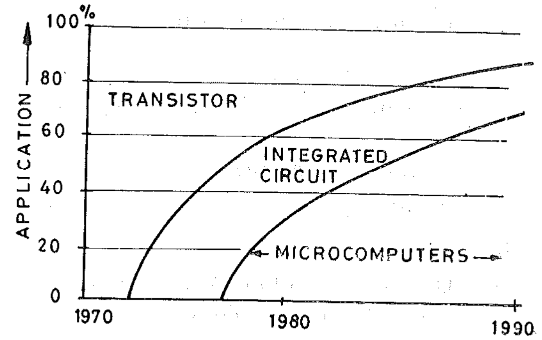


Fig. 43.21. Three generations of technology in components of Static Protection Systems and Control Circuits.

Table 43.4. Digital Circuits and their Functions

Digital Multiplexers.	To produce an output which is a combinational function of input variables.
Encoder and Decoder	If number of inputs is greater than the number of outputs, the combinational logic circuit is called encoder. If the number of inputs is lesser than the number of outputs the combinational logic circuit is called decoder. Encoders and Decoders are used in form of MSI, LSI, VLSL. They are used in CPU of computers and microprocessors.
Sequential Logic Asynchronous and Synchronous	Digital sequential logic circuits and programmable system incorporate these types of logics. In synchronous sequential logic, synchronising signal is used to control the instant at which transition occurs in the state of system. In Asynchronous sequential logic, the state is determined by the functin of the circuit and the value of the logic signal. External synchronising signal is not used.
Clocked Flip-Flop.	Basic elements in synchronous sequential circuits is Flip-Flop.
Memory function	Memory elements are essential in sequential systems and digital signal processing. Semiconductor read and write memory is very widely used.
Memory device.	It should be possible to uniquely address the memory device that stores a binary digit. It should be possible to read the state of every stored binary digit. — ROM Read Only Memory. It is not possible to change the state of binary digits in the ROM. It is nonvolate. — RAM Random Access Memory. In this, we can read/write in to the memory. Memory is denoted by number of bits *e.g.* 8 bit memory Large arrays of ROM and RAM are used in programmable systems counters.

It is a sequential circuit which can go through specific sequence of states and which perform a state of transition on each occurrence of input. A counter can be used directly to count a number of occurrances of input by converting the series of inputs into a prescribed sequence of states such that at any point the current state or current may be output or read. Counter can also be used to form a coded sequential output.

PART II
MICROPROCESSOR BASED PROTECTIVE RELAYS

43.24. MICROPROCESSOR BASED RELAYS

The microprocessor based relays have become commercially acceptable. They are preferred for complex protection and control systems. In microprocessor based relays the digital processing unit is a **Microprocessor. Most recent protective relays for overcurrent protection, differential protection, distance protection and Substation Protection etc. are with 8 bit or 16 bit microprocessors.**

The basic principles of Digital Relays described with the help of Fig. 43.19 are applicable to microprocessor based relays also.

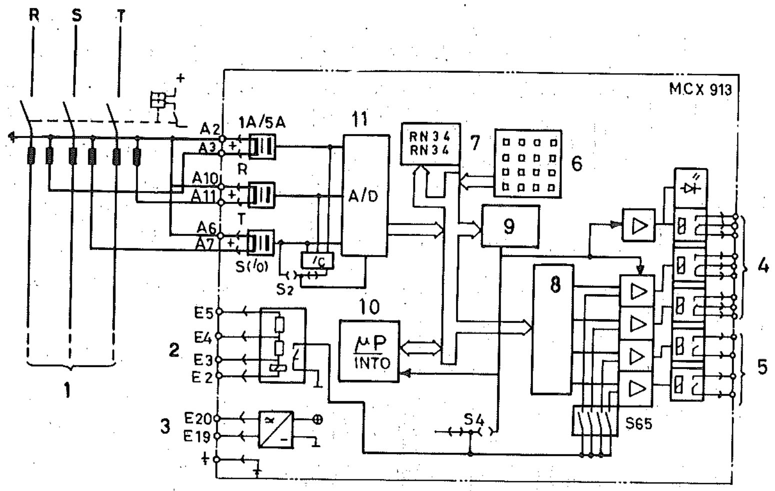
Microprocessor is now used for Protection, fault recording, fault locating, data monitoring and several other functions which were earlier performed by analog or digital systems.

43.25. DESCRIPTION OF A MICROPROCESSOR BASED PROTECTIVE RELAY FOR MOTOR PROTECTION * (*Courtesy* : Brown Boveri, Switzerland.)

Fig. 43.22 gives a block diagram.

The CTs feed current to A/D converter (11). A/D converter gives digital signals to the microprocessor (μP - INT - 0) and software matrix block 8.

* The description is for pinpointing the various special provisions available with a typical microprocessor based protective relays.



1. Protected unit
2. Blocking input
3. Aux. supply 26 to 312 Vdc or 80 to 242 Vac
4. Aux. signalling relays
5. Aux. tripping relays
6. Keypad
7. Display
8. Software matrix
9. Watch dog
10. Microprocessor
11. A/D Converter.

Fig. 43.22. Block-diagram of a Microprocessor based overcurrent relay/overload relay for Motor Protection.
(*Courtesy* : Brown Boveri)

The microprocessor (10) performs the digital signal processing.

Protective Functions

In the motor protection relay under description, several conditions are analysed by the microprocessor (11) and the software martix (8). The protective functions in this relay include :

(*i*) Earth fault protection
(*ii*) Negative phase sequence protection (I_2)
(*iii*) Short circuit protection ($I \gg 2$)
(*iv*) Overcurrent protection ($I >$)
(*v*) Protection against low loads ($I <$)
(*vi*) Thermal overload protection ($\Delta\theta$)
(*vii*) Motor starting protection (I-START)

The protective relay has to decide logically the conditions under which the tripping signals are to be given via auxiliary tripping relays (4).

Signalling and trips by Software Martix

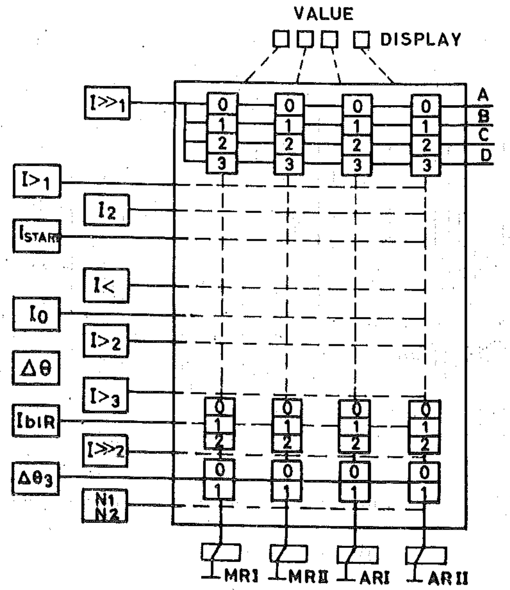
Refer Fig. 43.23. The signalling and tripping logic is provided in the software matrix (Block 8) which gives command to auxiliary tripping relays (4), and auxiliary signalling relays (5).

The software tripping matrix has been shown in Fig. 43.23.

The user is able to freely select those starting and tripping signals that are significant for his plant and can allocate them freely to the various auxiliary relays by means of the software tripping matrix (Fig. 43.23).

Two signalling and two tripping relays are provided. For each relay a number can be used to select one of the four following modes of operation for each protective functions.

— No action (0)	...	Condition A
— Signalling a start	...	Condition B
— Signalling a trip (2)	...	Condition C
— Signalling a trip with self retention (3)	...	Condition D



a no output *b* aux. signalling relay I or II
c aux. tripping relay I or II *d* aux. tripping relay I or II with latching
* This allocation is possible for all protection functions excepting $\Delta\theta_3$ and I_{bLR}

Fig. 43.23. Software tripping matrix in Block 8 of Fig. 43.22.

Signalling of a start : Persists until the particular setting is exceeded.

Signalling of a trip : Appears when the time-lag belonging to the particular protective function has expired or as soon as a set temperature rise or a set number of permissible starts by the motor has been exceeded. Exception : if tripping with self-retention is selected, the trip annunciators only drop out when the reset button has been pressed.

Memory of Tripping value and time run

The memory for the tripping value and time run contains the value of the current and the time-lag of the particular function at the instant the last trip took place. If no trip takes place, the last time run of the particular function will be memorized. The memory for tripping value and time-run is volatile, *i.e.* in the event of failure of the auxiliary supply, its contents are lost.

Self Monitoring

The microprocessor based relay Fig. 43.22 is provided with self monitoring (watchdog) (8). The relay is continuously and comprehensively monitored by the watchdog and test software, any faults which do occur (e.g. failure of components) are detected at once. Thus, without adversely affecting the availability, it is largest possible to dispense with periodical testing of the relay.

Testing Facilities

For periodical testing of the relay one of the test sets may be used. For testing, the active part is withdrawn from its casing and inserted in a test casing wired to the test set. It is also possible to test the relay in its built in state.

Settings and Memories

Settings can be made quickly and at any time *i.e.* even where the relay is in operation. Once values have been set and memorized, they are retained even if the auxiliary supply should fail (memorizing in NOVRAM = Non-/volatile Random Access Memory)

For the parameters of the MCX 91 relays there are two memories.

— Background memory (non volatile, NOVRAM) in it the valid parameters are memorized, *i.e.* the protective relay always operates only with the settings memorized in NOVRAM.
— Foreground memory (volatile)
— when the auxiliary supply is switched on, or with a special command, the parameters from the NOVRAM are copied in the foreground memory. There they can be altered as desired with the "vary" key. The displayed value is always the value in the foreground memory.

43.26. ADVANTAGES OF AND SPECIAL FEATURES OF MICROPROCESSOR BASED PROTECTIVE RELAYS

Compared to the earlier hard wired analog and digital relays, the programmable microprocessor based relays have superior features which include the following :

1. Ability to Combine a large number of protective and monitoring functions in a single relay unit. *e.g.* in Fig. 43.22 the relay unit combines 7 main and 3 auxiliary function.

In the protection schemes of earlier generation separate relay units were necessary for each main function resulting in more number of units, more wiring, lesser reliability.

2. Measured values of variables are processed digitally by microprocessor. The digital processing by microprocessor gives several abilities to the protective relay. These abilities include

— Combinational logic
— Use of on-line processing of variables
— Programmable feature, etc.

3. **High level of Flexibility.** Various protective functions can be freely selected and allocated to the various auxiliary relays by means of software tripping matrix (*e.g.* Fig. 43.23). The same relay can give tripping signals, blocking signals, starting signals, signals to fault recorders etc. *The relay meets the most complex protective and monitoring requirements.*

4. The memory of the relay enables the relay to retain the values of variables responsible for tripping, time taken by relay to operate etc.

The values can be displayed on demand by the operator. Thereby the nature of fault, fault current etc., are precisely known.

5. The relay can *digitally display* values of on the current, voltage etc. by pressing appropriate button on the face. Thereby need of each instrument is eliminated. *Microprocessor design provides precise measurement and compact panel.*

6. *Comprehensive self monitoring self checking feature.* The relay with self monitoring feature can monitor its own circuits continuously and if any internal component has failed, indication is obtained. The relay also indicates functional readiness to operate. In relay with self checking property, the performance can be checked by the operator during periodic maintenance.

7. **Increased Reliability due to self-checking**

Recent Microprocessor based digital relays provide digital sensing and logic Processing. The microprocessor checks itself, the peripheral circuitry, RAM, NOVRAM, EPROM memories and the power supply. In addition, it monitors the AC inputs using A/D converter calibration check inputs. It also monitors LOP (Loss of Potential) and LOI (Loss of Current). The self checking feature improves the reliability of microprocessor based digital relays.

8. **Data Interface Access - Increased Communication ability**

Microprocessor based digital relays can have interface with (communicate with (1) Other Relays (2) Protected equipment (3) Control and protection devices in the substation. By means *via Relay Interface Unit* (Fig. 43.19, Block 3). The data and control commands can be exchanged. The sequence of software events which occur in the processing unit (Fig. 43.19, Block 7) can be stored in the memory and subsequently displayed and obtained in the form of printed output. The periodic maintenance requirements are reduced.

9. **User friendly yet highly capable**

Microprocessor based relays are easy to apply, operate and use. Yet they are highly capable *e.g.* a modern microprocessor relay for transmission line protection has two four digit alphanumerical displays that show up 62 separate settings, seven LEDs and it is easy to access stored data and easy to input new-data.

10. Relay provides Fault designations and informations. The metering display shows three phase voltages, current, load angle. The data is accessible through front panel display. Pre-fault voltage, current and load angle are also displayed when desired. The relays can be hooked to a microprocessor based fault recorder and fault location indicator.

11. **High Speed.** High speed relays Minimum tripping time of 12 millisecond and maximum of 32 millisecond are available for line protection. A typical microprocessor based relay for line protection takes 20 millisec.

43.27. BLOCK DIAGRAM OF A MICROPROCESSOR BASED DISTANCE RELAY FOR PROTECTION OF TRANSMISSION LINE

Refer Fig. 43.24. The Microprocessor (Block 7) is the 'heart' of the protective system. It is a Intel 80 C/96 Microprocessor with a 16 bit microcounter operating at 10 MHz. The program memory (Block 7-1) is in separate easily replaceable EPROM chips. The subsystem (Block 7-2, 7-3) also includes volatile Read-Write memory (RAM) for working storage and Nonvolatile RAM (NOVRAM) for storing the settings and targets when the relay is deenergized.

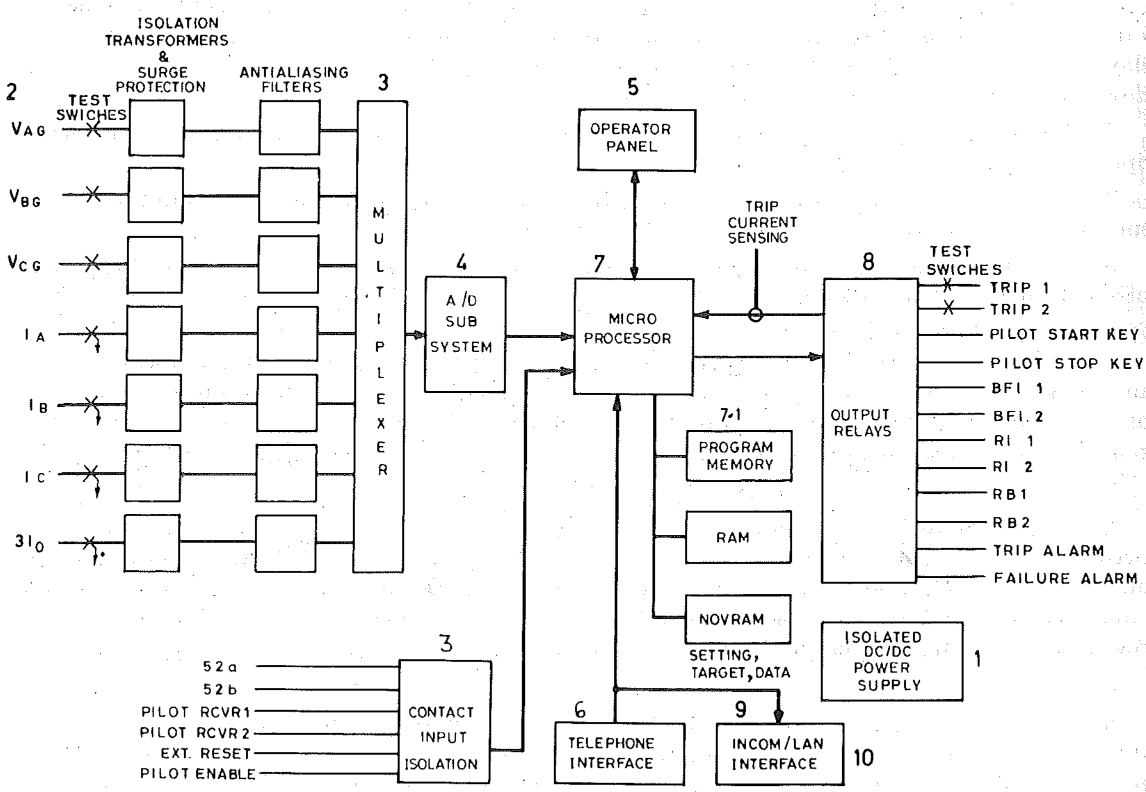


Fig. 43.24. Microprocessor Base Distance Relay.
(*Courtesy* : Westinghouse, USA)

Included on the processor board is the A/D conversion system (Block 4) and a Multiplexer (Block 3). The AC input quantities (Block 2) of 4 currents and 3 voltages are analogue multiplexed to a single sample/hold circuit. The sample/hold output is fed to an A/D subsystem (Block 4) which yields in bits dynamic range. *Each AC input is sampled 8 times per power cycle.* (1/60 sec for 60 Hz)

The filter module (Block 3) contains seven low pass filters which provide anti-aliasing functions and conditioning of incoming AC currents and voltages.

The interconnect module (Block 3) is used for interconnecting with other modules electrically. Located in the interconnecting module are optical isolatops (52A, 52B). External Reset Pilot Enable, Receiver 1, Receiver 2 Inputs)

Block 1 is DC/DC convertor power supply for the communications interface and alarm relays. Power supply provides isolation from station battery system and includes overcurrent and undervoltage protection. A failure alarm relay monitors status and provides loss of power indication. The alarm relay is normally picked up, but will drop when the processor defects a problem on upon loss of DC. The power supply (Block 1) generates DC voltages of – 24, + 5, – 12, + 12 V DC. These are made available for various circuit.

Test switches between Block 2 and 3 provide high quality test and isolation functions and permit convenient entry of current and voltage quantities trip circuits are also wired out through these switches to provide for cut out of trip circuits.

Measurement and Range

The relay provides three zone distance measurement with optional pilots for additional zones. The operating characteristic for each zone is variable mho characteristic for all types of faults.

A single Relay weighing 16 kg and size 19" wide 7" high and 14" deep can perform several functions as mentioned in sec. 43-26 the table.

PART III
MICROPROCESSOR

Microprocessor and Microcomputer

A microprocessor (μP) is a single package containing logic circuits of Central Processing Unit plus various amounts of 'depositary and conduit' logic which surround a central processing unit (CPU). Thus the word 'microprocessor' means a specific electronic logic and packaging. The electronic logic must be equivalent to the central processing unit. The package must be a single chip, packaged as a Dual Line in package (DIP). A chip in electronic language means microscopic electronic circuits created on a tiny silicone piece. The chip is mounted in a Dual In-line package (DIP). The microprocessor has a single chip in a DIP.

In contrast a microcomputer has specific electronic logic incorporated in a variety of packages including several DIPs and additional electronic circuits.

Microcomputer is a product which contains all the functions found in a digital computer.

Microcomputer may have one of the following configurations.

1. One chip microcomputer has a single chip packaged in a single DIP and other electronic circuits. Such a microcomputer is called single chip Microcomputer.
2. Multi-chip microcomputer has two or more chips and other electronic circuits.

Microcomputer must have a central processing unit.

A Microprocessor is remarkably like a Central Processing Unit of minicomputer. Hence, it is generally called Central Processing Unit. However though there is a remarkable similarity between the Microprocessor and a CPU, they are different products.

Microprocessor is a single package containing the processing logic. Adding the memory, interface circuitry and other external devices converts the microprocessor into a microcomputer.

The advanced manufacturing techniques of microelectronics and digital sciences have resulted in the development of microprocessors. The complete 'central processing unit' of a minicomputer is constructed on a single integrated circuit (chip) and is put inside a single package called a microprocessor. The earlier microprocessor built during 1970's were without incorporation of memory in the same chip. Further advances of VLSI (Very Large Scale Integrated Circuits) have resulted in ICs containing CPU and memory units which form the heart of a single chip microprocessor/microcomputer.

Microprocessor is an advanced programmable logic device designed to carry out specific processing function. Microprocessors are used in digital protection systems for processing the digital information.

A Microprocessor has minimum number of components. Once developed, a microprocessor based relay is manufactured into several tens of thousands of units. Therefore extra items are avoided.

Memory Size

The binary digits are combined to form a code which can represent a number. The primary level at which binary digits are grouped within the processor is the most important design characteristic of a microprocessor/minicomputer/computer and is referred as 'word size' An 8-bit microprocessor processes the binary data in eight binary digit units. The memory is organised into 8 bit units.

The memory organised into 8-bit units is visualised as follows :

By common convention the bits of a word are numbered from right (0) for the low order bit) to left (7 for the high order bit).

The following table gives the distinction between microprocessor, minicomputer and computer.

Table 43.5

Type of processor	*Word size —bits*						
Microprocessor and Microcomputer	4,	6,	8*,	12,	16*		
Minicomputers	6,	12,	16@	18,	24	32	64
Large Computers	4,	16,	18,	24,	32@	64@	

* Most common for digital protection systems.
@ Most common for Digital computers.

Byte

An 8-bit data unit is called a byte. A byte is most universally used data unit in computer terminology. It is used when there is no 8-bit data word.

A 16-bit microprocessor will often have memory words interpreted as two bytes.

Memory Addresses

There are subtle differences between the use of memory in a microprocessor and in minicomputer. In a minicomputer memory is simply a sequence of individually addressable RAM words, with address beginning at 0 and ending at some large number which depends on the size of computer memory.

In microprocessor based product for example a microprocessor based relay, program memory is in a separate replaceable EPROM chips.

EPROM means Erasable Programmable Read-Only Memory.

By inserting required EPROM chips, special information that EPROM is to hold is inserted into the micro processor based relay.

An EPROM like PROM holds the information indefinitely once it has been programmed. One can read contents of an EPROM again and again.

RAM (Randon Access Memory) is for working storage. It is generally understood to mean a memory with both read and write capability in which the location can be accessed in any random sequence. In a very simple case, in a 8 bit microprocessor, 8 RAM chips may implement 8-bit read/write memory words with each chip contributing to a word.

RAM chip memory size is commonly described as 'M × N' chip, where M is number of accessible units on a memory chip and N is the number of bits in each addressable unit.

Non-volatile RAM (NOVRAM). Non-volatile RAM (NOVRAM) is used for storing settings and targets when relay is de-energised.

43.28. ARCHITECTURE OF A MICROPROCESSOR

Fig. 43.25 gives a block diagram of a Microprocessor Based Minicomputer.

Microprocessor and Microcomputers are programmable and they perform the digital processing operations as per the program.

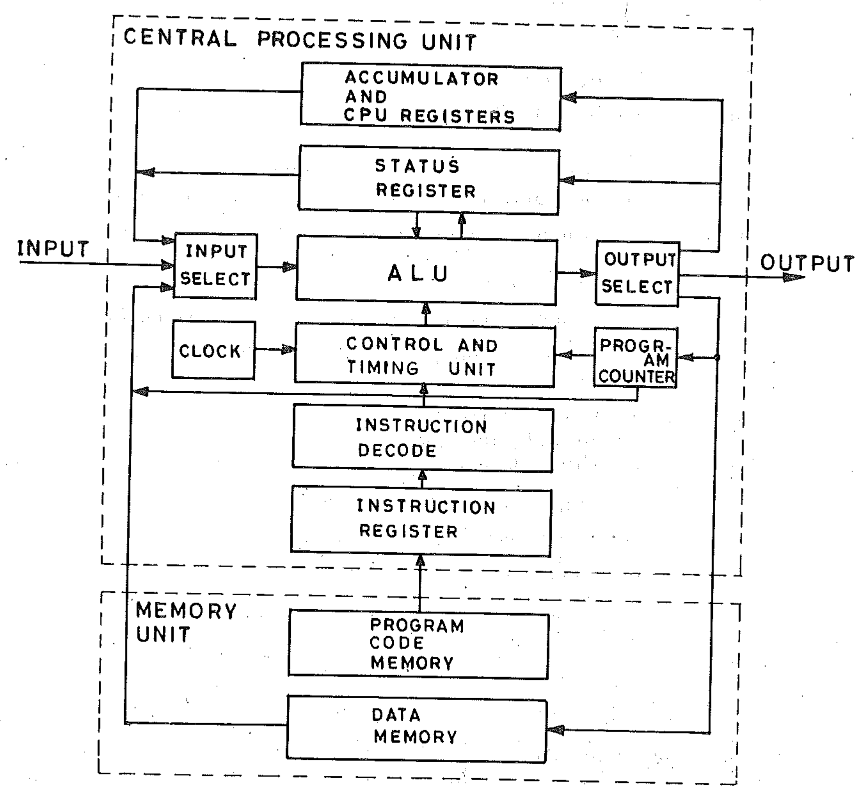


Fig. 43.25. Block diagram of a Microprocessor based Minicomputer. The central Processing Unit corresponds to a microprocessor. Refer Fig. 46.5.

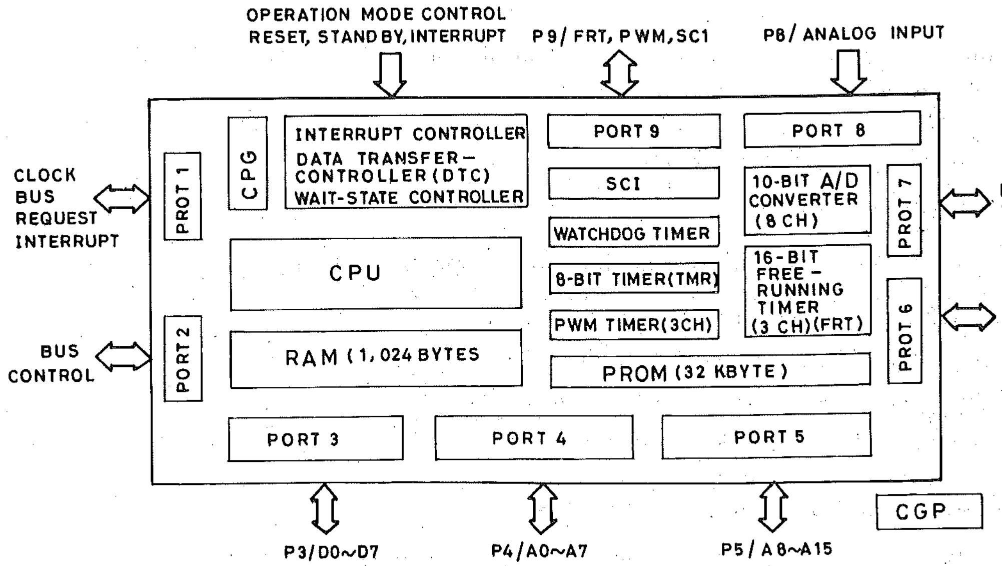


Fig. 43.26. Block diagram of a 16-bit Microprocessor.
Courtesy : Hitachi, Japan.

Table 43.6
Specifications of a 16-Bit Microprocessor*
(Type H8/532 Hitachi)

CPU	16-bit H8/500 CPU
ROM	32 kbytes (PROM/Mask ROM)
RAM	1,024 bytes 8-bit free running timer : 3 channels (3 input capture registers, 6 output compare registers)
Timers	8-bit timer : 1 channel (2 compare registers) PWM timer : 3 channels Watchdog timer : 1 channel
SCI	1 channel (Asynchronous mode/Synchronous mode)
A/D	Resolution : 10 bits, 8 channels (Single mode/scan mode)
INTC	3 external interrupts 19 internal interrupts Priority : 8 levels
DTC	On-chip data transfer controller
WSC	ON-chip wait-state controller
I/O ports	57 input/output ports 8 input ports 84-pin PLCC
Package	84-pin windowed lCC 80-pin OFP
Process	CMOS 1.3 μM

PWM : Pulse width modulation
SCI : Serial communication interface
PLCC : Plastic leaded chip carrier
QFP : Quad flat plastic package.

* Ref. Fig. 43.26 for Block diagram of this Processor.

Central processing unit (CPU) shown in Fig 43.25 is the microprocessor. CPU contains ALU, control and Timing Unit, number of important Registers and Timing clocks etc.

A microprocessor may lack some of the peripherals, but it must have a CPU. The logic of each microprocessor differs widely from the other.

Program are instruction codes which are input to the CPU as means of the sequential operations to be performed. Program is stored in the memory.

CPU Registers fetch the stored data from the memory. The registers are also called **accumulators**. An 8 bit microprocessor has 8 bit accumulator. CPU usually operates on the data contained in register rather than accessing memory words directly.

ALU (Arithmetic Logic Unit). The actual data manipulation within the CPU is handled by the collective logic called ALU. The ALU processes binary data. A 8-bit microprocessor has a ALU which will operate on a 8 binary digits. ALU performs the following functions.

(*i*) Boolean addition (*ii*) Boolean operations
(*iii*) Complement a data (*iv*) Shift a data word one bit, etc.

CPU is built up to perform more complex processing of data.

Control Unit (CPU). The sequence of logic operations of the ALU is determined by the control unit. The CU is in turn is driven by the contents of the instruction register.

Control and Timing Unit. The basic operations of the ALU of the microprocessor or CPU are governed by the control unit (CU) and Timing Unit (TU). The control and Timing Unit gets reference timing signals from external clock and CPU.

[The data from data lines is placed by RAM is addressed memory word. RAM is able to extract the data from addressed memory word and place it on external system bus data line].

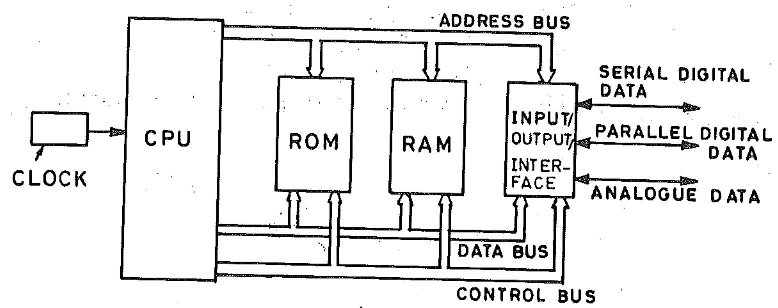


Fig. 43.27. Architecture of System Buses in a Microprocessor based system.
CPU = Central Processing Unit (Microprocessor)
ROM = Read Only Memory
RAM = Random Access Memory (Called Read and Write Memory)

Bus lines are classified into four categories (Fig. 43.27)

(*i*) Address bus
(*ii*) Data bus
(*iii*) Control bus
(*iv*) Clock, power, ground

Bus buffer. Usually the output signals are boosted by appropriate buffer amplifiers before connecting to the system bus lines. Buffer stores the information temporarily during the data transfer. (Fig. 43.28)

Address Bus. One system bus line is provided to every address. Normally more address bus lines are provided than the requirement, some for future requirement.

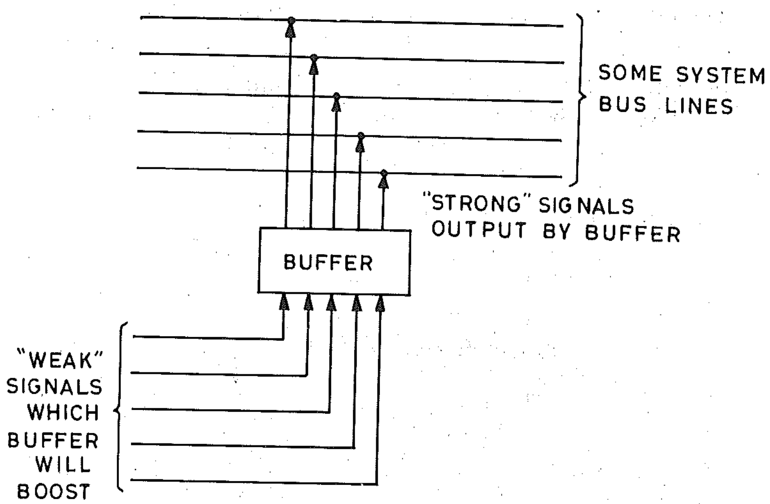


Fig. 43.28. Buffer amplifier weak signals before feeding to bus lines.

Data Bus. System bus line is provided for each data bit of the largest word. More data bus lines are provided, some for future requirement.

Control lines. Separate control line is provided to every control signal that may be output by or input to any device.

Clock, Power , Ground. There will be generally more than one clock signal on a system bus. Also a number of power lines are provided for the various devices.

Random Access Memory (RAM). (Fig. 43.29-A) It is often called read and write memory. A RAM takes off data from data lines of the external system bus and places this data in an addressed memory word. In addition a RAM must be able to extract data from the addressed memory word and places this data on external system data bus lines. Read/write memory is usually implemented a number of RAM chips, with each chip supplying one bit of the data word. Generators control signals necessary to operate various logic systems.

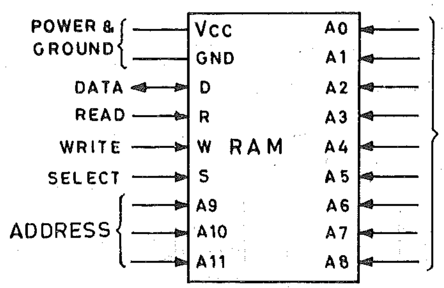


Fig. 43.29-A. RAM - Random Access Memory. Also called Read Write Memory (RWM).

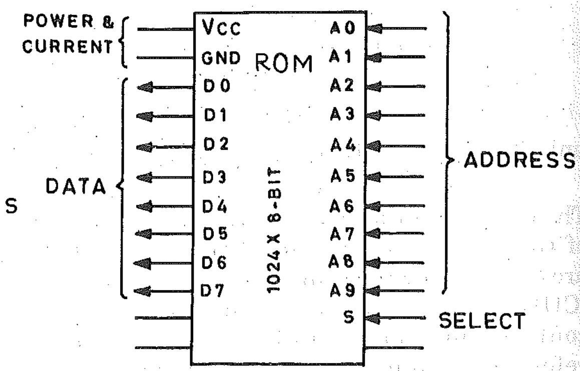


Fig. 43.29-B. A Read Only Memory.

The control unit (CU) is separated from Timing Unit in some microprocessor.

The control and timing unit controls the main operational cycle of the processor and is called the 'Instruction cycle'. The instruction cycle has two phases (1) Instruction fetch and (2) Instruction execution. During the instruction fetch the address of the next instruction is obtained from the program counter unit and transferred to the memory address register.

At the end of instruction fetch the CPU unit will have all the information required to control the instruction execution.

External Bus System

Fig. 43.27 illustrates bus oriented architecture of a microcomputer system. A bus denotes a channel along with data is transferred. It refers to the physical connection of data path. The architecture shown in Fig. 43.26 is preferred in many systems because it provides flexibility and easy expansion.

The Microprocessor (CPU), Read only Memory (ROM) and Read-Write Memory (Random Access Memory - RAM) Clock and many other devices each connect to a group of parallel signal lines which are collectively called as an external bus system.

Physically, the bus system consists of a number of parallel conductors. In todays microcomputers, these conductors are in the form of metal lines etched on a printed circuit card (PCC) *e.g.* There may be 100 parallel lines in an external bus circuit. These lines are assigned to different signals arbitrarity. The buses are not standard and each manufacturer has his own method of routing and naming to the bus system.

ROM in a Dual-in-package pins and signals ROM may have eight data lines for 8 bit word *via* which the contents of the addressed memory are transferred back to CPU.

Fig. 43.27 illustrates a single RAM Dual-In-Line package (DIP) and Fig. 43.26 shows the connections of an RAM, ROM and CPU by means of system buses.

Read Only Memory (ROM) A ROM device requires following input signals :

1. Address of memory words being accessed
2. A read control signal that asks the ROM device when to return the contents of the addressed memory words.
3. Power and ground.

Only output signals of an ROM device are 8 data lines for an 8 bit word through which the contents of the addressed memory word are transferred back to CPU.

ROM devices is built in the form of a Dual-In-Line package (DIP)

Fig. 43.30 shows connections of the ROM and Microprocessor with the bus-lines.

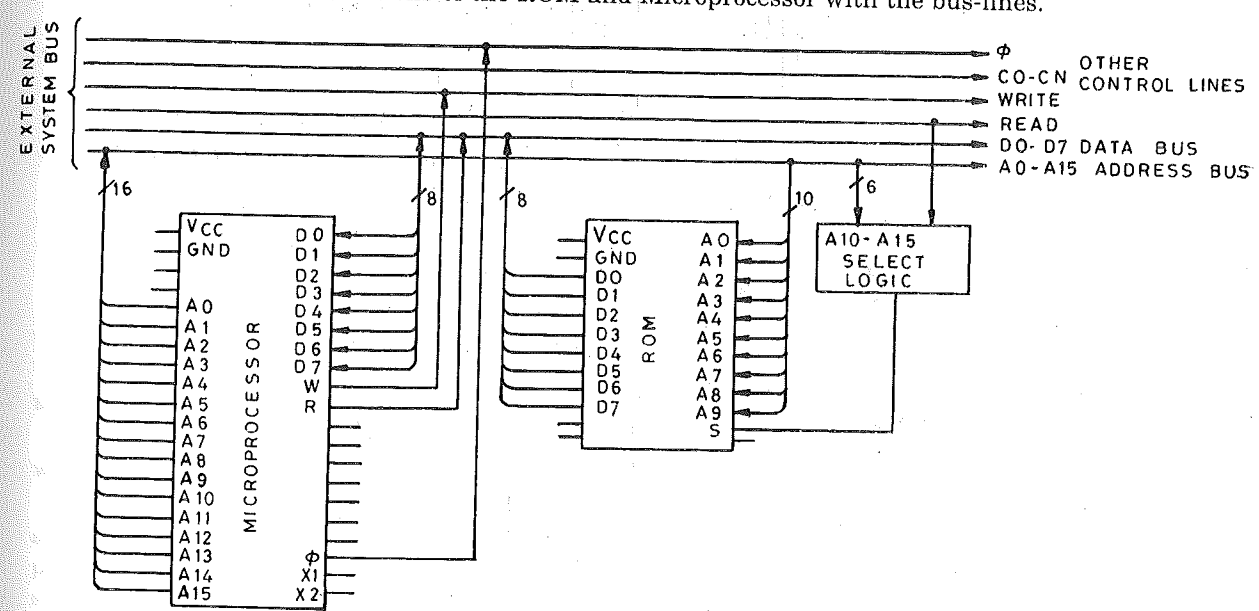


Fig. 43.30. Connections of ROM, Microprocessor with Data Bus, Address Bus, Control lines.

Input/Output. (Fig. 43.31 A, B) The transfer of analog data, digital data, between the CPU/RAM/ROM within the microcomputer and the external system beyond the microcomputer is called input/output and is designated as I/O.

The interface between the microcomputer system and the external logic must be clearly defined.

It must have provision to transfer the data and also control signals that identify the events as they occur.

There are many ways by which the data transfer at I/O state takes place between the external system and the microcomputer.

1. **Programmed I/O.** In this case the data transfer between the microcomputer and line external circuit is completely controlled by the microprocessor, or more precisely by the program fed to the microcomputer.

The microcomputer system requires input program based on which it waits for external logic input to place data in some predetermined location. I/O communicates with the operator *via*.Man Machine Interface (MMI).

Fixed Function Programmed Systems. Fixed Function Programmed Systems has a fixed program input and is constrained to perform a prescribed and fixed sequence of instructions. This

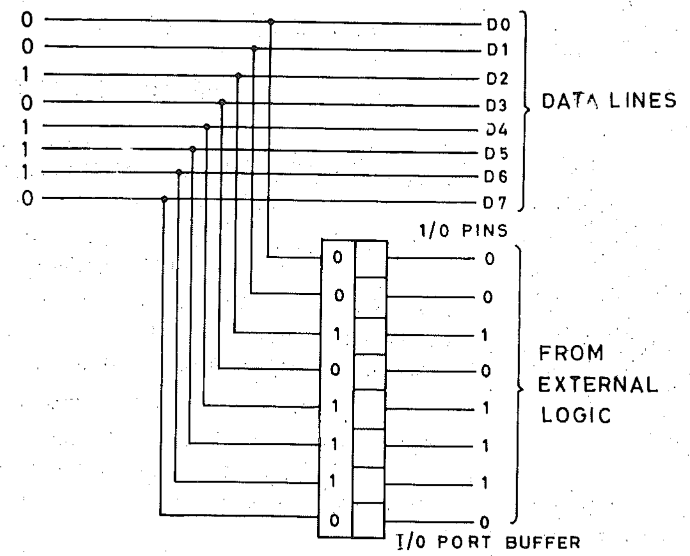


Fig. 43.31. (A). Input/Output, Port Buffer and Data Buses.

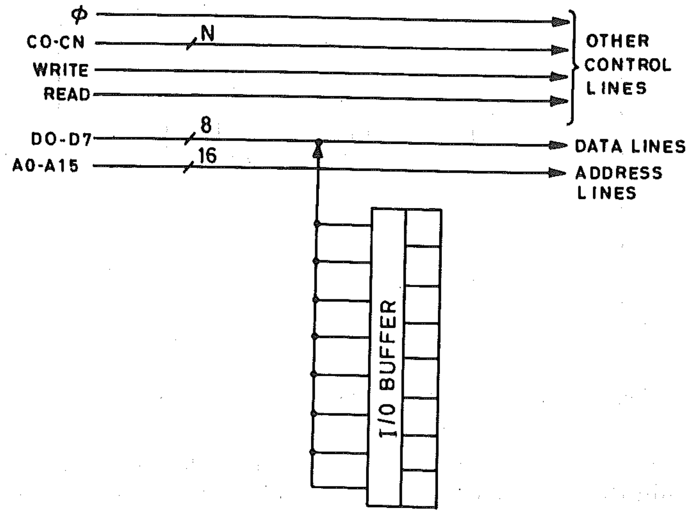


Fig. 43.31 (B). Various bus lines to which I/O Buffer is connected.

type of system does not have a capability of software control to select between two alternative sequences of instruction. The applications function of such system can be altered only by changing the program.

In microprocessor based relays, the fixed programmed system is preferred.

Program Memory is in separate easily replaced EPROM chips. The program memory chip is selected for using the relay for a specific application.

A fixed function programmable relay is forced to execute fixed sequence on instructions based on the programmed logic.

2. **Interrupt I/O.** Interrupts are a means for external logic to force the microcomputer system to suspend whatever it is currently doing in order to attend the needs of external logic. Most microprocessors have control signals *via* external logic which can demand the microprocessor attention. This signal is referred to as an interrupt request. The external logic asks the microprocessor to interrupt whatever it is currently doing in order to service the more immediate task.

3. **Direct Memory Access.** The form of data transfer at I/O stage allows data to move between the microcomputer memory and the external logic without the microprocessor in the data transfer.

High Performance IC Memories.

Microprocessor Unit with high performance are built with fast integrated circuit (IC) memories of following types :

DRAM	Dynamic Random Access Memory
SRAM	Static Random Access Memory
EPROM	Electrically Programmable Read Only Memory
SAM	Serial Access Memory

The microprocessors operated at 20 MHz has memories with access time in the range at 15 ns to 85 ns.

43.29. PROGRAMMING OF MICROPROCESSORS BASED RELAYS

Microprocessor based relays are supplied by the manufacturers for specific applications *e.g.*

— Microprocessor based relay for motor protection
— Microprocessor based relay for transmission line protection
— Microprocessor based relay for generator protection
— Microprocessor system for substation protection and control
— Microprocessor based fault recorder, etc.

The manufacturer furnishes guidelines for selection of the relay with appropriate built-in software for the microprocessor.

A single microprocessor relay has provided several possible combinations of protective functions with a wide range of setting for each function.

The desired protective function and range can be selected by means of '**Mode Selector**'. Mode selector is in several steps. The settings can be made easily in 'User friendly' manner. The programms are provided within the microprocessor by means of the programms module. The mode selection by the operator result in selection of protective function *via* the software matrix built in the relay (*e.g.* blocked, start, trip, signal, self retention etc. illustrated in Fig. 43.21. Block 6.

Disturbance detector detects disturbance in protected circuit and the trip output is possible only if the Microprocessor monitoring interface and Disturbance detector have ensured the presence of fault. Tripping due to malfunction of relay components is prevented.

In some more complex relays the programm is in the form of a separate chip on a EPROM memory. The manufacturer inserts the appropriate program in the relay. In case the application is changed, the program chip is changed.

43.30. SELF-CHECKING AND/OR SELF MONITORING IN MICROPROCESSOR BASED RELAY

The microprocessor based relays are designed for continuous self monitoring and/or automatic self checking.

By self checking/monitoring function the relay is in a position to report locally and remote, the likely malfunctioning/failing of internal component.

Fig. 43.32 illustrates the circuit of continuous monitoring subsystem in a microprocessor based relay. The vital component is a disturbance detector. This detects the disturbance in the protected circuit (transmission line) by measurement of negative sequence currents.

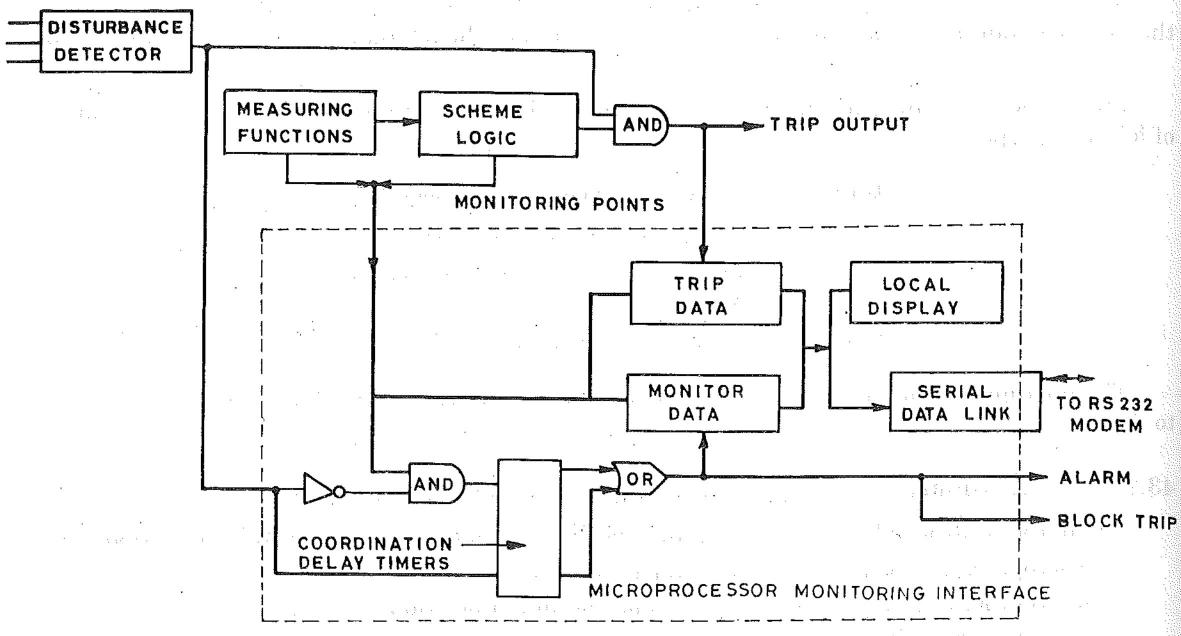


Fig. 43.32. Interface of self-checking of Microprocessor based relay with Disturbance Detector.

If the relay attempts to trip falsely because of malfunction within the relay, but the disturbance detector sees no disturbance in the protected line, the tripping is blocked. Fig. 43.33 shows principle of self checking in a microprocessor based relay. The important circuits which should be checked have been indicated.

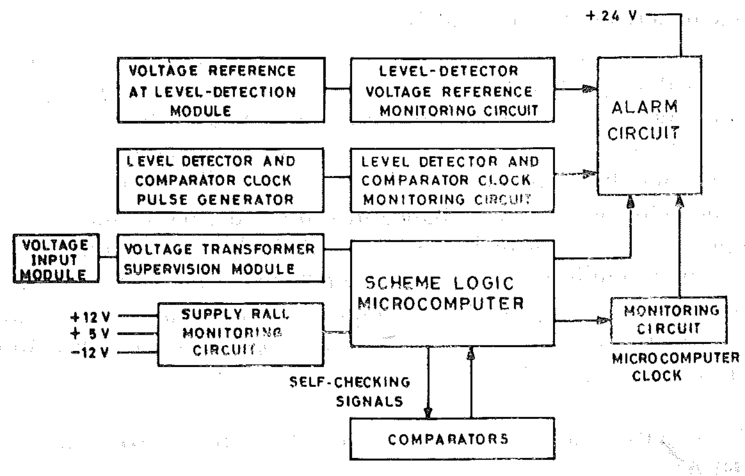


Fig. 43.33. Block diagram of self checking of critical components and circuits in a microprocessor based relay.

Digital relays are designed for continuous self monitoring or automatic self checking or both. There is a considerable difference between the manufacturers and the users regarding the choice between self monitoring and self checking feature.

Analog signals pass through the internal measuring-circuit selector and the A/D converter to the selection logic, together with the 16 units of binary event information added here, the data when passes to the memory, where it is decoded in "1 out of 512" form in a decoding and driver stage.

43.31. ON LINE MICROPROCESSOR BASED FAULT MONITORING

During recent years, fault monitoring systems are being incorporated along with the protective relays. Fig. 43.34 shows a block diagram of a Microprocessor based on line fault monitoring system. It provides for on line fault recording, which means that oscillograms are printed out immediately, on occurrence of a fault without restriction.

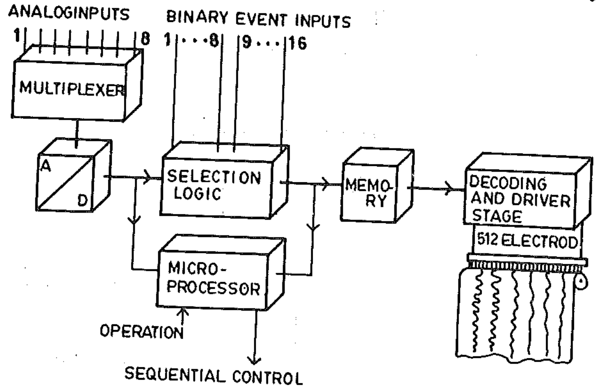


Fig. 43.34. On-line Fault Recorder. (*Courtesy* : Siemens)

Analog inputs are currents and voltages. These are multiplexed in the multiplexer and then converted into digital signals in A/D converter. The digital signals pass through selection logic which mixes in 16 binary events units before the information reaches the memory.

A microprocessor controls the operating sequence. It does not contribute data flow. Data flow is handled by systems hard wired logic. Microprocessor helps in comprehensive operating functions, automatic fault diagonals, recording and operating unit status.

If fault situation arises, the microprocessor activities the chart rotor motor and controls the recording sequence without interrupting the fault monitoring function.

The control system continuously scans all the elements for the inputs of commands (switches and keys) and enable program selection and parameter input by the user. A clock circuit (not shown in Fig. 43.24) is with a permanent lithium battery backup which provides the microprocessor with current time and data and also memory space for storing operating parameters in the event of power failure.

Metalized paper aluminium impregnated paper with a speed of 500 mm/s is used for recording. The current pulses are given by electrodes in 5 μs duration. There are 500 electrodes of 0.2 mm dia. Selected electrodes are activated in a sequence. Pulse sequence ensures recording of sinusoidal functions.

43.32. MICROPROCESSOR BASED FAULT LOCATORS

The distance protective relays for transmission line protects the transmission line from phase faults and ground faults. For permanent fault, the lines-men should reach the fault location and carry out the repair work (*e.g.* replacing procelains, faulty conductor, fallen tower, tree branch, etc.). To carry out these operations quickly the exact location of fault should be known from the terminal substations.

Fault Locator. It is an essential complement to distance protective relay for transmission lines and fault recorder. Fault locators are installed along with distance protection scheme and fault recorders. Fault locator measures and indicates accurately the distance between the substation and the point of fault.

Fault Recorder can also be combined with a fault recorder and printer for recording the distance to the fault and fundamental component of fault current prior to and after the fault.

Fault locator is connected to the secondary CTs and VTs of the line.

Under normal conditions, the fault locator monitors three phase currents and the ground current, voltage input signals continuously. The operation of the fault locator is with following steps (1) Data Collection (2) Starting of fault locator (3) Sorting of Measured Instantaneous values (4) Filtering of Measured signals (5) Determination of type of fault (6) Solution of fault equation (7) Prelocation of results.

The input analog signals are converted into digital signals in A/D converter and are stored in memory for every six cycles continuously.

When a fault occurs, trip circuit from the protective relay initiates the fault locator's calculation program. The prefault sample values and during fault sample values are used for calculating the distance of the fault. The calculation of distance is based on the principle of distance relays. The fault distance is shown as percentage of total line length on two digital front mounted LED display.

Fig. 43.35. illustrates the block diagram of the microprocessor based fault locator.

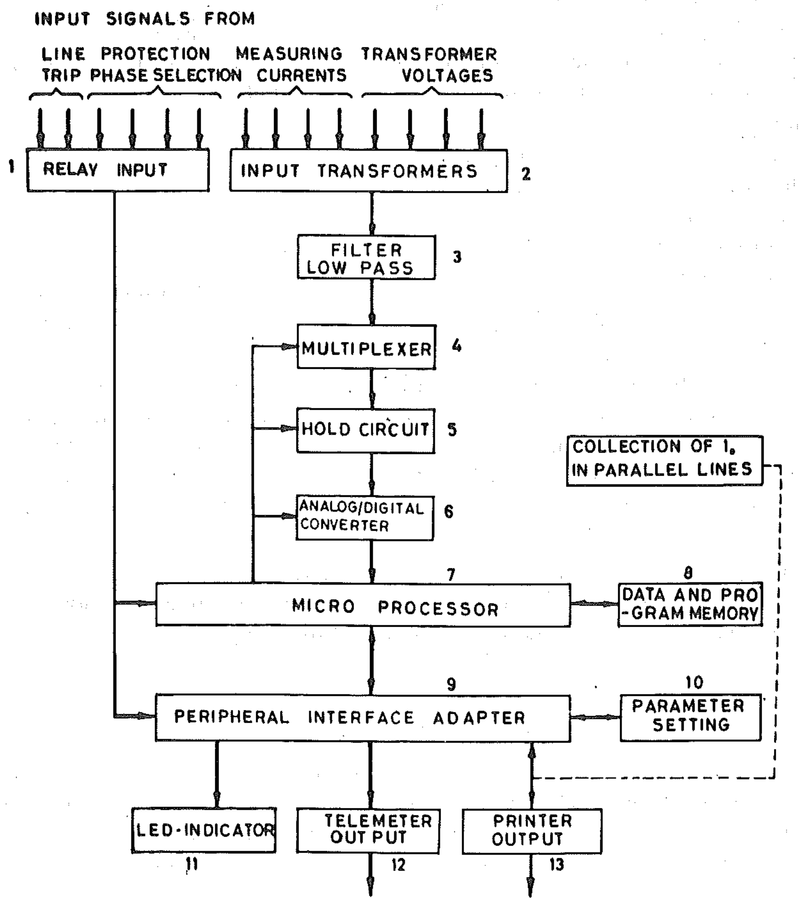


Fig. 43.35. Block diagram of a fault locator. (*Courtesy* : ASEA, Sweden)

Block 1 receives input signals from Line protection *viz* Line trip signals for first and parallel line, phase selection signals which identify the type and faulty phase. The receipt of tripping signal constitutes the starting signal for the fault locator. The measured values received by block 2 from cycles immediately prior to and during the fault are stored in the memory.

Block 2 receive line currents and line voltages from secondaries of CTs and VTs. Block 3 filters the input signals. Block 4 is a Multiplexer which is successive order transmits the signals (measured values) to Block (6) A/D convertor *via* hold circuit (Block 5). The function of the hold circuit is to retain signals for the period of time required by A/D. Converter to converter, the signals to digital form. The rate of measurement is chosen such that 24 measurements are made per cycle on each current and each voltage signal.

The measured digital values are routed through the microprocessor (Block 7) to the correct addresses in the memory capsules (Block 8). In these the values measured during the previous 9 cycles are stored.

Table 43.7. Functions of the Blocks of Fault Locator

Block No.	*Title of Fig. 43.35*	*Function*
1.	Relay Input	— To receive starting signal from distance relay. — Receive signal regarding faulty phases from distance relay — To give starting input to fault locator
2.	Input Unit	To receive signals from CT, VT and to feed to A/D converter *via* Filters.
3.	Low pass Filter	To filter the analog signals
4.	Multiplexer	To send the signals sequencially to A/C convertor.
5.	Hold	To hold the signal for a brief time period before sending to A/D converter.
6.	A/D Converter	To convert analog signal *s* to digital signals.
7.	Microprocessor	Processing of measured digital signals and calculate the fault distance. Feed output to printer, telemeter and LED indicator.
8.	Data and Program Memory.	— To store data for processing — To store programme in memory for instructions to microprocessor
9.	Interface adapter.	Connections between microprocessor and peripherals.
10.	LED Indicator	Indicates Fault Location and percentage of line length.
11.	Telemeter output	Give output data to Remote terminal unit *via* telecommuncation line.
12.	Printer output	— Presents results on printed paper indicating the following : 1. Values of current, voltage in faulted line prior to and during fault. 2. Timing of fault.

The Microprocessor (Block 9) executes the following control and calculating functions :

— Collection of measured values.

— Processes the measured values and calculates the distance between the CT/VT and the fault (proportional to calculated ZL)

— Present the percentage fault distance on the indicator.

— Feeds out calculated distance to the fault on an indicator.

— Returns to normal measuring mode after a line fault.

— Determines the type of a fault when a built in phase selector is used Block 8 constitutes the following Memories of the Fault Locator (FL).

— PROM Programmable Read Only Memory : for the control and calculation programs.

— RAM (Random Access Memory) for storing measured data and apart result during distance determining sequence.

The results are available to the operator in the form of alphanumerical printed output (13) and LED Indication (11). Results can also be transmitted by means of telemeter output (Block 12) to Remote Terminal Unit (RTU). Table 43.4 summarise the functions of various blocks within the fault locator.

43.33. PRINCIPLE OF FAULT DETECTION IN ON LINE DIGITAL RELAYS, FAULT LOCATORS AND FAULT RECORDERS

The 'On Line' protection control and monitoring system is connected to the power system *via* input Module and CTS/VTs.

The current and voltage in the power line are continuously monitored by the CPM system, cycle by cycle.

Measured signals stored in memory and the relationship between different time periods is illustrated. When a starting signal is transmitted to the relay, 9 cycles of information is already stored in the memory. About 2 cycles are stored after receipt of starting signal.

The microprocessor based device (Relay/Recorder/Locator) performs the one-line function as follows.

Input signals are received from secondaries of CTs and VTs. These are converted in digital form in the A/D module.

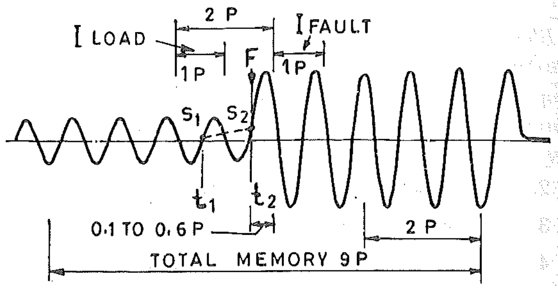


Fig. 43.36. Memory storage in a fault recorders and various microprocessor based relays.

Sample measurements. Sample measurements are taken for each measured quantity for every cycle of the waveform continuously (*e.g* 24 samples per cycle) Each sample is compared with the corresponding sample of previous cycle (Fig. 43.36). When the power line is healthy sample S_2 of next cycle will have the same value as the previous sample S_1.

If a fault occurs in the power line during the period S_1 to S_2, the measured value of the sample (S_2) will differ from corresponding value of previous cycle S_1.

If the difference S_2-S_1 is in excess of permitted tolerance, the presence of fault is detected. Thereby the PCM system follows the sub-routine corresponding to a faulty condition immediately and the following actions are taken.

1. Protective relay initiates tripping and autoreclosing actions.
2. Fault recorder gets starting signal from the protective relay and performs the recording of currents and voltages of approximately 9 cycles, which include 2 periods prior to the fault Fp.
3. Fault locator is also initiated and indicates the location of fault in terms of percentage of the length (*e.g.* 40% L).

In the normal conditions, the memory keeps information about currents and voltages for every 9 cycles continuously in the event of a fault the record of 9 cycles is derived from memory by the microprocessor and given to the printer output, telemeter output.

Application of Protection Relays

We now know that the main objectives of Relay Protections are :

— To ensure protection of the apparatus & equipment connected to the system
— Protection of persons and property
— To separate the faulty system immediately from rest of the system so as to facilitate the continued operation of the healthy part of the system.

So far, in previous sections, we have studied the various types of relays & their functions. We shall now give an example of its application in a power plant.

Protection Requirements of a Power Plant

The generator, transformer, Switchgear, feeders & other equipment are provided with protections against all possible electrical faults usual for such networks, the main objectives being to avoid damage to the equipment as well as to avoid unwarranted trippings.

The fault possibilities/abnormal conditions which are normally encountered during the operation of such equipment or system are :-

(*a*) **Generator-Transformer Units**

— Earth faults in stator and rotor
— Multi-phase faults in stator windings & transformer windings close to terminals
— Single phase ground fault in transformer windings & its terminals

— Inter-turn faults in transformer windings
— External symmetrical & asymmetrical short-circuits
— Pole slipping conditions
— Negative phase sequence currents
— Over-loading of stator windings
— Over-loading of rotor windings
— Breaker failure
— Over-voltage/under voltage conditions
— Sudden energisation of the machine when standstill
— Insulation leakage at HV/LV terminals of Generator Transformers
— Ground fault in generator excitation circuit
— Loss of excitation
— Asynchronous condition of generators
— Under frequency conditions
— Reverse power flow conditions
— Transformer over fluxing
— Incepient Transformer faults
— High oil & winding temperatures.

(*b*) **Station Auxiliary, Unit Auxiliary & Excitation transformers**

— High temperature of windings
— Over-load
— Multiphase faults in windings & at terminals
— Earth faults
— Under voltage

(*c*) **HV, Switchgear**

— Multi phase and earth faults in buses & bus-coupler
— Mal-operation of circuit breakers
— Multi phase and earth faults in bus-coupler

(*d*) **Shunt Reactor (Where ever Connected)**

— Multi phase and earth faults in windings and at terminals
— Mal-operation of circuit breaker
— Oil Level low
— High Winding temperature

(*e*) **HV Cables**

— Multi phase and earth faults

(*f*) **Feeders (Transmission lines)**

— Multi phase and earth faults
— Over voltage conditions
— Mal-operation of circuit breakers

The protection system shall identify the above abnormal condition/faults and ensure a fast and selective protection of generators, generator transformers, 420 kV Switchgear equipment, Feeders, Cables and other connected equipment/switchgear with a fast separation of the faulty part & accordingly following electrical protections are provided for each equipment.

Generator & Transformer

87G	Generator Differential
64G1/64G2	95% & 100% Stator Earth Fault
64R*	Rotor Earth-Fault
46G	Negative Phase Sequence Current
37G	Generator Reverse Power
49S	Stator Thermal Over-load
21G	Generator Back-up Distance Protection for external faults
40G	Loss of excitation
78G	Pole slipping
59G	Generator Over-voltage
81 U/O	Under/Over Frequency Protection
27/50G	Dead Machine
60G1, 60G2	Voltage Balance Scheme for VT circuit failure
87T	Generator Transformer Differential
51GT	IDMT O/C Protection for Gen. transformer
64RT	REF Protection for Gen. transformer
51NGT	Gen. Transformer Neutral Grounding Back-up Protection (IDMT O/C relay)
99GT	Generator Transformer Over fluxing
98T	Monitoring of Insulation of HV bushing for Gen. Transformer
59T	Monitoring of Insulation of LV bushing for Gen. Transformer
87GT	Overall Differential Protection for Gen. and Gen. Transformer
50U/51U	Instantaneous and IDMT O/C Protection for UAT.
64RU*	Restricted E/F Protection for UAT
51NGU*	O/C & E/F/Neutral Back up Protection for UAT
50E/51E*	Instantaneous & IDMT O/C Protection for Excitation Transformer.
50EI/51EI*	Instantaneous & IDMT O/C Protection for Independent Excitation system
50S/51S	Instantaneous & IDMT O/C Protection for SAT
64RS*	Restricted E/F Protection for SAT
51NGS*	O/C & E/F/Neutral Back-up Protection for SAT
50Z	Local Breaker Backup Protection
63T*	Buchholz Relay for Gen. Transformer
95G	Split Phase Protection for inter-turn fault

Protections for HV Buses

87AB	Differential main & stand by Protection for each bus bar (High impedance or low impedance)
50Z	Local Breaker Back-up Protection (for bus coupler)

Protections for Shunt Reactor

87R	Differential Protection
50Z	Local Breaker Back Up Protection
64RR	Restricted Earth Fault Protection
21R	Reactor Back Up Distance Protection

Protections for HV Cables for each feeder

85	Differential Protection
67/67(N)	Directional Over current and earth fault back-up protection

Protections for Transmission line

21L1	Line Distance Protection Main-I
21L2	Line Distance Protection Main-II
59L1	Over Voltage Protection
59L2	Over Voltage Protection
79L	Auto Reclose Relay
50Z	Local Breaker Backup Protection

Summary

Microprocessor comprises a Central Processing Unit (CPU) of a digital Computer. A microprocessor is housed in a DIP.

Microprocessor performs digital data processing functions in protective relays. Microprocessor based relays are being increasingly used for busbar protection, line protection, motor protection etc.

Special features of microprocessor based relays are their self-checking properties, multi-function capabilities, memories, facilities for disturbance recording, fault locating, external communication interface, etc.

Microprocessor based relays are becoming commercially successful and they are replacing earlier analog relays.

QUESTIONS

1. Describe by means of a block diagram the various essential components in a Digital Relay (Ref. 43.19).
2. Explain how a decimal number is represented in a Dual (Binary) Code (Fig. 43.20).
3. State the various components in a Microprocessor based Microcomputer (Fig. 43.25*a*).
4. Explain the term 'Microprocessor' and State its functions.
5. Explain the bus system in a Microprocessor based minicomputer (Fig. 43.26). State the functions of
   (*i*) CPU (*ii*) ROM
   (*iii*) RAM (*iv*) Interface
6. State the functions of following components in a Microprocessor based relays.
   (*i*) Buffer (*ii*) Program Memory
   (*iii*) Data Memory (*iv*) ALU
   (*v*) Register (*vi*) Clock
   (*vii*) Control and Timing Unit
7. State and Explain the special features in a Digital Relays as compared with analog relays.
8. Explain the function of Self checking/Monitoring feature in a Microprocessor based Relay.
9. Explain the function of fault by recorder by means of a block diagram.

43-C

Modern Protection System — A Summary

43.34. INTRODUCTION

Electrical Relays made the operation and performance of any electrical installation safe & to a large extent hazard free. The first generation electro-mechanical relays or devices performed their main functions of alarm or trip effectively. However, their utility was limited to those functions only for which they were intended *i.e.* trip & alarm to. It also involved lot of hard wire connections ; Subsequently with the passage of time, Static relays & integrated circuits were introduced for to most of the protective functions.

These static & integrated circuits could were successful in combining few protective relay functions but it did help much in reducing the quantum of cables or in information exchange from the relay to the operator the control room.

The advent of technology has now made it possible to talk to the relays, this has become possible through modern numerical relays. These relays not only perform protection functions, but also provide auto-closing, measurements, disturbance recording & above all communication facilities & software programmable through standard functions and algorithms. They can be integrated with Modern Supervisory & Data Acquisition (SCADA) System.

43.35. NUMERICAL RELAYS

Numerical relays are digital devices designated to carry out protection functions of various electrical equipment such as generator, transformer, transmission lines, motor etc. As opposed to the electro mechanical and static relays which take the inputs from the current and voltage transformers directly, the digital relays/numerical relays take the transduced form of the current and voltage outputs from the current and voltage transformers normally in the range of 0-20 mA or 4-20 mA. The analog signals so taken as inputs are filtered squared and digitized. The protection algorithms take these digitized inputs to perform the calculations necessary to achieve the protection functions for which that particular numerical relay is designed.

Numerical relays are being used for electrical protection functions such as:

— Differential protection
— Overvoltage protection
— Stator earth fault protection
— Negative sequence protection
— Distance protection
— Restricted earth fault protection
— Over current protection
— Thermal overload protection
— Loss of excitation protection
— Over excitation protection etc.

All the protection functions which can be achieved with the static protection relays are achieved by the numerical relays also with the same or better accuracy. The numerical relay achieves a lot many functions such as man-machine communication, connectivity to remote computers, networking etc.

In addition to the above, there are some protection functions, which are achieved with a lot of difficulties using static circuits, and still the final outcome is not quite satisfactory. One example

of such a protection is negative sequence current function. This protection is designed to operate above a particular limit of unbalance in the load connected to a generator. The negative sequence currents result in heating of the rotor of the generator. The analog circuit for this protection requires 120° phase shifting network, which requires sinusoidal currents. In a numerical relay, the negative sequence current is calculated by summing sampled of R, Y and B taken at 0°, 240° and 120° intervals respectively. From this summing, the I_2^2 value is calculated. This value is zero even for non-sinusoidal currents as the three phase currents for the same amplitude to wave shape and also they are phase displaced by 120°.

Advantages of numerical relays

— The output of one current transformer can be used as input to many protection functions.
— The burden on current transformers is substantially reduced due to a very low burden imposed by digital circuits.
— As many functions are done by one numerical relay, a lot of space is saved by eliminating independent relays for each of the functions.
— The settings can be done from a remote computer or the local MMC.
— The service and faulted values of the relays can be accessed either from a remote computer or from the local MMC.
— Selection from a variety of characteristics is possible. This will be useful if one feels the necessity to alter the originally selected curve/characteristics based on operation experience.
— Some of the latest numerical relays share the same hardware for protection of different electrical equipment such as generator, transformer and transmission line. Only the specialized software required for carrying out these protection functions needs to be changed. This helps in reduction of inventory, as most of the modules are interchangeable among the different numerical relays.
— The software can be programmed/modified at site to change the tripping logics such as inclusion of timer, changing of tripping sequence etc. Due to self-supervision feature, internal faults in the relays are detected as and when they occur and as such, there is no necessity of periodical testing of these relays.
— Due to reduction of number of components and also due to the fact that circuits are provided with built in control to prevent mal-functioning, the numerical relays will also increase the security compared to the static relays.
— Recursive algorithms can be achieved easily on a numerical relay. But, precise tuning is required in case of analog circuits.

However, with all the above advantages & convenience they offered, the numerical relays, suffered from one major draw back *i.e.* not understanding & interpreting the language of other relay, if the vendor is different. This problem is referred to as Protocol matching. This problem arised because now a days, the majority of the protection and control equipment is available with vendor specific hard ware-oriented solutions which has given rise to a large number of manufacturer oriented communication Protocols making it in convenient & costlier to make the two systems of different manufacturers to communicate with each other:, even devices belonging to different generations from the same manufacturer cannot communicate with each other & to make them do so involved an appreciable expenditure.

43.36. TRADITIONALLY SEPARATE NETWORKS

Over the years, networks have been developed to respond to the different information flows and control requirements involved in different processes. The usual corporate IT network supports traditional administrative functions and corporate applications, such as human resources, accounting, and procurement. This network is usually based on the Ethernet standard.

The control-level network connects control and monitoring devices, including programmable logic controllers, PC-based controllers, I/O equipment, and human-machine interfaces (HMIs). This network, which has not been Ethernet in the past, requires a router or, in most cases, a gateway to translate application-specific protocols to Ethernet-based protocols. This translation lets information pass between the control network from the field and the corporate network infrastructure.

The device-level network links the field I/O devices, sensors, transducers and actuators, etc. Inter-connectivity between these devices was traditionally achieved with a variety of field buses such as Device Net, Profibus, and Modbus. Each field bus has specific power, cable, and communication requirements, depending on the application it supports. This has lead to a replication of multiple networks in the same space and the need to have multiple sets of spares, skills, and support programs within the same organization.

Instead of using multiple networks architectures, Industrial Ethernet can unite an organisation's administrative, control-level, and device-level networks to run over a single network infrastructure as shown in Fig. 43.39. In an Industrial Ethernet networks, field bus-specific information that is used to control I/O devices and other manufacturing components is embedded into Ethernet frames. Because the technology is based on industry standards rather than on custom or proprietary standards, it is more interoperable with other network equipment and networks.

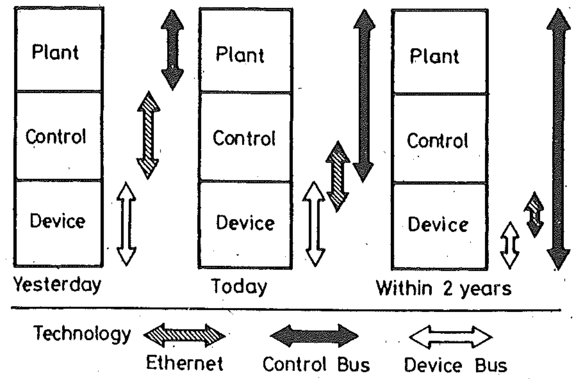


Fig. 43.39. Growth of Ethernet to device level.

43.37. ETHERNET JUST A PHYSICAL LAYER STANDARD

Ethernet has been successfully used in the office automation for many years. It was originally invented by Robert Metcalf at Xerox in 1973 and patented in 1976 and further promoted by Digital and Intel. It is typically used in office local area networks that later evolved into the IEEE 802.3 specification. Today this technology can deliver performance from 10 Mbps (10 BASE-T) to 10 Gbps (10 gigabit Ethernet) on twisted pair copper cables to fibre optics.

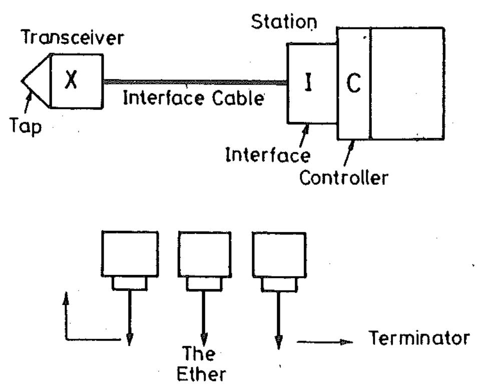


Fig. 43.40. The famous original concept drawing of Ethernet by it's inventor.

The industrial world is now catching onto Ethernet as a supplement to existing field buses. In an Industrial Ethernet network, field bus-specific information that is used to control I/O devices and other manufacturing components are embedded into Ethernet frames. Industrial Ethernet usually requires more robust equipment and a very high level of traffic promotization as compared to traditional Ethernet networks in a corporate data network.

Ethernet is achieving more acceptance in the industrial automation world, but Ethernet in itself is just a physical layer standard and various type of application layer protocols can be used on this medium.

43.38. THE IEC's INITIATIVE

Currently IEC too has the following three distinct standards for network access, protection equipment and tele-control :

— IEC 60870-5-101 Companion standard for basic tele-control tasks.

— IEC 60870-5-103 Companion standard for the informative interface of protection equipment.

— IEC 60870-5-104 Network access for IEC 60870-5-101 using standard transport profiles.

IEC-60870-5-103 standard is generally in the monitoring direction for protective equipment but various manufacturers use the private range of the standard through a few extensions defined by the so-called German VDEW-recommendations for implementing some of the control functions through IEC 60870-5-103. The nonuniformity of using the private range by various manufacturers in their own way makes the products non inter-operable with the products with IEC 60870-5-103 standard.

With a goal to provide uniform standard for inter control center communication and substation to control center communications, a new international standard called IEC 61850 - "Communication Networks and systems in substations" has been developed. This will provide inter operability & free allocations functions between the electronic devices (IEDs) for protection, monitoring, metering, control and automation in substations ; This new standard is expected to provide optimally designed systems in terms of functional performance, cost, availability, expandability and maintenance.

IEC 61850 divides the data into logical groups, viz., protection data, switchgear data (status data), measurement data, supervisory control, power transformer, etc. All the functions performed in a substation are split into small entities, which communicate with each other. These entities or objects called Logical Nodes contain all the function related data and their attributes to be communicated. All the Logical Nodes of a common application are grouped in Logical Devices. This function model has to be a complemented by a physical device model, which describes the common properties of the device. On occurrence of any change of state, IED multicasts a highspeed message called Generic Object Oriented Substation Event (GOOSE) message.

The data model including its services is mapped to a mainstream communication stack consisting of MMS, TCP/IP, and Ethernet.

The IEC 61850 standard is now near its completion. Utilities and manufacturers have been involved in the standardisation work since the beginning, and have taken part in pilot projects and interoperability tests, which have been positive.

IEC61850 is a single, global and future-proof standard for substation communications which safeguards the investment of the end user because the development of the communication network is independent of the development of applications. Besides it provides the benefit of the latest communication technologies for enhancing the performance of the controls and protection system.

Details of IEC 61850 are described separately.

IEC 61850 - Concept, benefits & design

1. Concept

The main goal of IEC 61850 is Interoperability, *i.e.* the ability of Intelligent Electronic Devices (IEDs) from one or several manufacturers to exchange information and to use it to perform the functions in an automation system. The approach of IEC 61850 is to subdivide functions into the smallest possible objects called Logical Nodes which communicate with each other. Each logical node has its own set of data. The data are exchanged following the rules which are called services. These generic data and services are mapped to a mainstream communication stack comprising Manufacturing Message Specification (MMS), Transmission Control Protocol/Internet Protocol (TCP/IP), and Ethernet.

Operational information and configuration information are transferred in client-server mode. Operational information, such as status and control, is standardised and of medium priority. Configuration information, such as file transfer and changing settings, is of low priority. Two further types of message are exchanged under stringent real-time conditions. The first type of message contains one or a few bits of information and is mostly for blocking, release, tripping, indication of position of switchgear in automatic sequences, interlocking, protection as well as for other data exchanges between peer devices. This type of message is called Generic Object-Oriented Substation Event (GOOSE). The other type is for Sampled Values, used for sending streams of analogue data such as current and voltage samples. To attain proper performance, both types of message are mapped directly to the Ethernet; the second layer of the seven-layer communication stack, without going through MMS or TCP/IP.

The Abstract Communication Services Interface facilitates the mapping of the generic data and services to the communication stack. The applications and the stack are thus separated, allowing the communication technology to be upgraded and the existing databases of the applications to be left intact. This feature makes the standard IEC 61850 future-proof.

IEC 61850 also states the engineering process and makes available the Substation Configuration description Language (SCL). The precise descriptions of the IEDs, the substation configuration and other configuration related information can be read by any tool compatible with the standard.

The standard also defines conformance testing of products so that interoperability may be checked, ensuring the successful integration of devices from a variety of manufacturers to form a seamless system.

2. Benefits

Compared to IEC 60870-5-103, DNP3 or proprietary communication protocols, IEC 61850 offers much more benefits to the utilities. Some of these benefits are immediately tangible on the substation automation systems. Other benefits will take time to transpire because:

- Getting the full value of the standard requires
  - accepting new designs e.g. moving away from master-slave to client-server communication,
  - using process bus,
  - new ways of managing assets.
- While the technology starts best on greenfield sites, a large proportion of the projects involve mixing legacy existing devices with new ones, and the benefits due to the new devices can only show themselves to a limited extent.
- Staff often have a natural reluctance in accepting a new technology.
- Not all the advantages of interoperability can be appreciated at the start.

IEC 61850 is applicable within a substation. Work is in progress to extend this method of standardising communication up to the control centres, aiming at seamless data-flows from the processes in the switchyard to the highest control level. The substation data-model is already harmonized with the Common Information Model from IEC 61970. The result of this standardisation will further simplify the specification of substation automation systems.

3. Design

The design stage aims at defining the data flow and infrastructure of the substation automation system.

The underlying Ethernet layer facilitates the design process through the use of mainstream communication technology. For example, Ethernet switches possessing properties such as collision avoidance, optimisation of the messages being transmitted, priority management, are readily available and need no further detailed design, except any additional precautions in the electronics-hostile substation environment. Re-using an existing Ethernet infrastructure also means little new design work. Transferring both real-time data, settings and disturbance files on a common 100 Mbit/s network means fewer systems to deal with. Note that the co-existence of critical and non-critical data on a common network running on other protocols such as RS485 at 64 kbit/s, is impossible without compromising one type of data or another.

Allowing fast peer-to-peer data transfers by means of the multicast messages, Ethernet eliminates physical wiring between devices of most suppliers in substations, for instance, for interlocking and co-ordination of disturbance recorders. This reduces the amount of hardware and also permits adjusting the system easily in the future. For example, changing a database is much simpler than adding wires which sometimes need take voltage insulation into consideration. New automation schemes can be accommodated and would incur little design work.

The availability, or reliability, of master-slave systems from most suppliers depends largely on the availability of the master device. IEC 61850 systems have no master devices. Client-server communication enables redundancy to be built in easily. It improves the flexibility of the system. A new client such as a permanent local voltage regulator for several transformers or a temporary remote monitoring device of a transformer, can be added to the initial design of the system through the same software. Client-server communication leads to better performance, as data are spontaneously sent to the client without the polling from a master device. Data transmission may be initiated by the change in the data value, and the change criteria may be adjusted from remote.

4. Installation and commissioning

The installation and commissioning stage aims at testing the system to make sure it works according to the specifications.

The Ethernet network can be checked by means of standard tools. The Internet Protocol (IP) enables messages to be routed to a remote location where commissioning personnel can view system status and give expert advice. When the system under test spreads over an entire substation, testing staff can plug the Human Machine Interface to any Ethernet switch close to the equipment under test and see simultaneously all the alarms, control points, etc. Likewise, a simulator can be connected to the Ethernet to check the automation functions when the corresponding devices are still not available.

Some built-in features of the standard also directly facilitate commissioning. For instance, when a sensor is not yet in service, the Substitute function can be used to emulate the data it would have given to the IED corresponding to the sensor. The management of the function mode *i.e.* the capability to remotely set a function 'in' or 'off' service, together with the client-server communication, offers the opportunity to progressively commission the system. This means the commissioning of a substation automation system can start before all the equipment is delivered to site.

5. Operation and maintenance

The operation and maintenance stage aims at identifying the possible faults and failures, and at expanding the automation system in accordance with the overall business strategy of the utilities.

Independent of system operations, security can be built easily on communication level into the substation automation system with the aid of commercially available firewalls and routers which hide IP addresses. Operational information can be grouped and access limited to only designated personnel.

A substation automation system compliant with IEC 61850 can be easily extended to include new automation devices, primary equipment, bays or new voltage levels.

Although the management and the rules are yet to be defined, version numbers are mandatory in the SCL and the logical parts of an IED. Being able to keep track of versions of IEDs is vital to the long-term maintenance of the system, and this feature is unavailable in other communication standards.

6. Migration

General. Products compliant with IEC 61850 are available from 2004 onwards, and utilities wishing to

— safeguard investment
— seek a cost-optimised solution over the life-time of the substation
— improve the availability of the substation

are incorporating these products into their systems. The products are mostly introduced into the market step by step. For new substations which can be served by the available IEC 61850 compliant products, only IEC 61850 solutions are expected to be used and in this case, migration is largely irrelevant.

Some new substations may still need to be equipped with non-IEC 61850 devices. Utilities may also integrate IEC 61850 devices into existing substations through gradual replacement of old equipment or the addition of new bays. In these substations, equipment based on other communication standards/protocols needs to function together with IEC 61850 devices until.

Upgrading Devices. If supported by the original design, a device can be upgraded directly, for instance by adding a communication board and upgrading the software to some extent. The parameters would need to be adjusted. This looks attractive but would generally need relatively recent devices. The replacement of the communication system is beneficial only if retrofit or upgrading at the station level is also carried out, and this means some additional engineering work.

For this migration strategy, two options are possible. One option is upgrading all the devices in the substation. The other option is upgrading the devices step-by-step in groups, for example, according to bays. For the second option, the old and new devices would need to function together.

Existing Systems side-by-side with IEC 61850 System. Many existing automation systems already support a number of protocols. The IEC 61850 devices are brought in initially as adding an additional protocol. The IEC 61850 system is gradually expanded and the other non-IEC 61850 devices are phased out. In general, there is a central point to which systems running on different protocols are connected and where protocol conversions take place. To keep the migration costs low, it is important that the protocol conversions are performed only at this point. Special attention shall be paid to distributed automation with real-time constraints because many legacy protocols are unsuitable for handling time-critical data.

In a substation with merely a few devices running on another protocol, the newly incorporated IEC 61850 system would be the dominant system. The existing system would be considered as a subsystem, *i.e.* a data server of the IEC 61850 system. It may support some standard protocols such as DNP3 or IEC 60870-5-101. The existing system is connected to the IEC 61850 system via a gateway that carries out the protocol conversion between the legacy protocol and IEC 61850.

In general, these migration paths are suitable for the following three scenarios:

— The automation system is replaced step by step.
— The substation is extended with additional bays.
— Individual devices are upgraded step by step in groups.

43.39A. Numerical Control & Protection Unit

The numerical control unit (REC 316*4) is a compact multi-functional unit belonging to PANORAMA. It is designed for the control, metering, monitoring, automation and protection functions of MV and HV transmission systems. Simply programmable standard functions from a comprehensive software library and a powerful and last function block language make the unit a user-friendly and extremely flexible terminal.

The control of switching objects is performed with the highest possible supervision and safety. A large selection of protection functions reduces the number of necessary devices in HV bays through the combination of control and backup protection functions in one unit. The integrated autoreclosure function can be utilized by both main protection devices.

The closure of the circuit breaker can be supervised by a synchrocheck function. Motor busbars can be switched on with phase synchronization by a fast switch-over function.

A part from the operating asset protection in cooperation with function block engineered modules using the CAP 316 to tool, the multi-configurable frequency function allows the generation of intelligent load shedding automatic. Automatic network restoration is enabled by integrating the REC 316*4 into a station control system.

For metering the quantities current, voltage real power, apparent power and frequency are available. In addition the transmission of energy counting impulses to the control system is possible. The recording of disturbances switching operations and analog results of protection functions is performed by the integrated disturbance recorder.

The REC 316*4 belongs to the generation of fully numerical control and protection terminals *i.e.* analogue to digital conversion of the input variables takes place immediately after the input transformers and all further processing of the resulting numerical signals is performed by microprocessors and controlled by programs. Resulting numerical processing ensures consistent accuracy and sensitivity throughout its operational life.

REC 316*4 is noted for its process interface, satisfying the highest EMC requirements as well as for the standardized serial interfaces for integrating into a control system. This enables an information exchange both in a vertical direction with systems of higher order and in a horizontal direction between various bay control units.

Because of its compact design, the very few hardware units is needed, its modular software and the integrated continuous self- diagnostic and supervision functions, it ideally fulfills the user's expectations of a modern control and protection terminal at a cost effective price. The availability of a device, *i.e.* the ratio between its mean time in service without failure and the total life, is most certainly its most important characteristic.

The menu-based HMI (Human Machine Interface) and the terminal's small size makes the tasks of connection, configuration and setting simple. A maximum of flexibility, *i.e.* the ability to adapt the protection for application in a particular power system or to coordinate with, or replace units in an existing control and protection scheme, is provided by the extensive library of standard functions and the powerful function block engineering. The free assignment of input and output signals is enabled via the HMI.

The hardware concept for the digital control unit comprises four different plug-in units, a connecting mother PCB and housing (Fig. 43.40A) :

— analog input unit
— 1 to 4 binary input/output units
— connecting mother PCB
— central processing unit
— power supply unit
— housing with connection terminals.

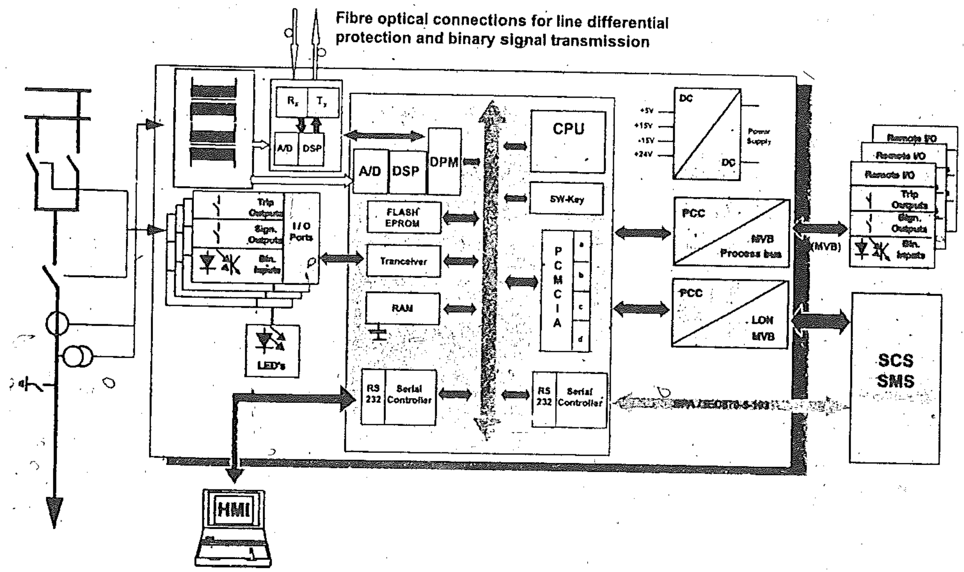


Fig. 43.40A. Hardware platform overview.

In the analog input unit an input transformer provides the electrical and static isolation between the analogue input variables and the internal electronic circuits and adjusts the signals to a suitable level for processing. The input transformer unit can accommodate a maximum of nine input transformers (voltage, protection current or measuring transformer).

Every analog variable is passed through a first order R/C low pass filter on the main CPU unit to eliminate what is referred to as the aliasing effect and to suppress HF inter ferences (Fig. 43.40B). They are then sampled 12 times per period and converted to digital signals. The analog/digital conversion is performed by a 16 Bit converter.

A DSP carries out part of the digital filtering and makes sure that the data for the protection algorithms are available in the memory to the main processor.

The processor core essentially comprises the main microprocessor for the protection algorithms and dual-ported memories (DPMs) for communication between the A/D converters and the main processor. The main processor performs the protection algorithms and controls the local HMI and the interfaces to the station control system. Binary signals from the main processor are relayed to the corresponding inputs of the I/O unit and thus control the auxiliary output relays and the light emitting diode (LED) signals. The main processor unit is equipped with an RS232C serial interface via which among other things the protection settings are made, events are read and the data from the disturbance recorder memory are transferred to a local or remote PC.

On this main processor unit there are two PCC slots and one RS232C interface. These serial interfaces provide remote communication to the station monitoring system (SMS) and station control system (SCS) as well as to the remote I/O's.

It has one to four binary I/O units each. These units are available in three versions :

(*a*) two auxiliary relays with two heavy-duty contacts each, 8 optocoupler inputs and 6 signalling relays.

(*b*) two auxiliary relays with two heavy-duty contacts each, 4 optocoupler inputs and 10 signalling relays.

(*c*) 14 optocoupler inputs and 8 signalling relays.

According to whether one or two I/O units are fitted, there are either 8 LED's or 16 LED's visible on the front of the terminal.

Both analogue and binary input signals are conditioned before being processed by the main processor. As described under hardware above, the analogue signals pass through the sequence input transformers, shunt, low-pass filter (anti-aliasing filter), multiplexer and A/D converter stages and DSP. In their digital form they are then separated by numerical filters into real and apparent components before being applied to the main processor. Binary signals from the optocoupler inputs go straight to the main processor. The actual processing of the signals in relation to the protection algorithms and logic then takes place.

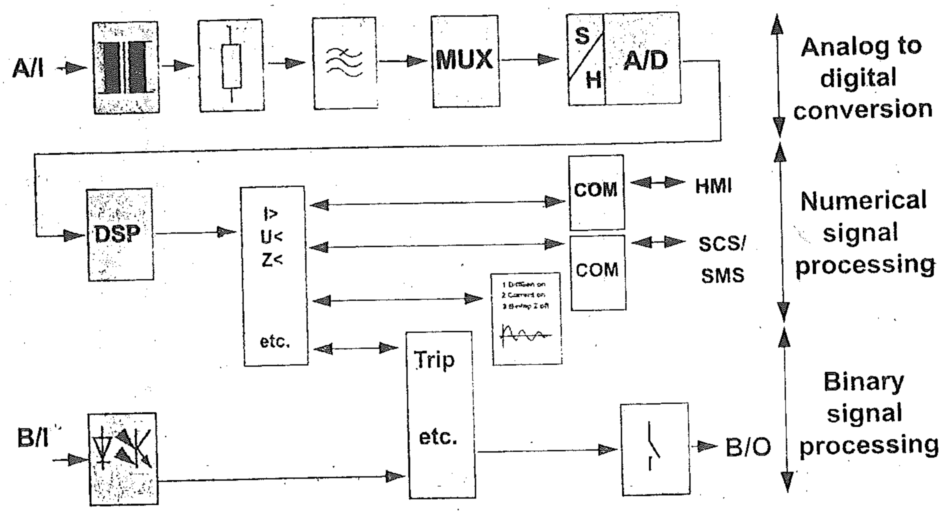


Fig. 43.40B. Signal data flow.

43-D

Microprocessor Based Substation Protection Control and Monitoring

Introduction to Microprocessor based Control, Protection and Monitoring — Two hierachical levels — Substation level, Unit Level, Functions in substation level, Functions in Unit levels — Integrated communication — Summary.

43.39. INTRODUCTION

The basic variable related with the Substation protection, Control and Monitoring include the following :

(*i*) Current (*ii*) Voltage,
(*iii*) Frequency (*iv*) Time,
(*v*) Power Factor, Reactive Power, Real Power, Temperature.

The electrical energy is transferred from large generating station to distant load centres *via* the various substations. In every substation certain measurements, supervision, control and protection functions are necessary. Every substation has a control room. The relay and protection panels and control panels are installed in the control room. The various circuit breakers, tap changes and other devices are controlled by corresponding control-relay panels. In a small independent substation, the supervision and operation for normal service can be carried out by the operator with the aid of analog and digital control systems in the plant. The breakers can be operated by remote control from the control room. During faults and abnormal conditions, the breakers are operated by protective relays automatically. Thus the primary control in substation is of two categories:

1. Normal routine operation by operators command.
2. Automatic operation by action of protective relay and control systems.

Traditionally, the protective system comprising of relays and circuit-breakers was almost independent of control system for tap-changer control, voltage control, data logging, data monitoring and routine operations. This concept is shown in Fig. 26.1 for Circuit-breaker control and Fig. 25.1 for Protective Zone. In traditional substation control the three functions (1) Protection (2) Control (3) Monitoring are not integrated fully. In modern interconnected systems, the functions are interlinked by means of digital processing devices and power carrier communication links (Fig. 43.1).

43.40. EQUIPMENT TO AUTOMATIC CONTROL SUBSTATIONS

The following equipment (either fixed-wired or/and programmable) is used for various tasks in Network Automation.

(*i*) data collection equipment
(*ii*) data transmission telemetric equipment
(*iii*) data monitoring equipment
(*iv*) data processing equipment
(*v*) man/machine interface.

The data (information) regarding various power-system variable is necessary for effective supervision, operation and control. This data can be broadly classified as :

(*i*) data regarding generating plants and power station

(*ii*) data regarding transmitting stations (sub-station)

(*iii*) data regarding conditions of supply region, receiving stations.

The equipment for protection, control and automation are installed in control rooms of :

(*i*) Load Control Centres (*ii*) Transmission substations

(*iii*) Distribution substations (*iv*) Generating Stations.

These control rooms are in communication *via* Power Line carrier communication system (PLCC).

In traditional hard wired systems are relays and circuit breaker operate during abnormal operating conditions. The routine and emergency control functions are performed at individual 'Unit' level systems with the held of substation equipment such as circuit-breaker, tap chargers etc. Control and monitoring functions are performed by separate equipment installed on respective panels. Each substation control room operated almost independently all instructions are received from Control Centre *via* Power Line carrier telephone communication link.

With the present trend and availability of powerful microprocessors a low price, the protection, control and monitoring system in substations have undergone a radical change. The system architecture now includes, microcomputer based digital system control protection and monitoring systems installed in (1) load control centres (2) Substation control Room (3) Generating station control room. The control and protection systems are integrated and there is interaction and information transfer by means of communication channels.

43.41. TWO SUBSYSTEMS IN SUBSTATIONS

The protection control equipment in a substation are to be treated as two sub-systems :

1. Control System 2. Protective System.

For many reasons, it is desirable to have two separate systems as above.

The relay protection system should acquire the data independently, process it, evaluate it and take action to perform protective tasks (tripping).

The different events are reported to the control system as well as protective system. Both the systems must, therefore, co-operate closely with one another.

In modern substation, these functions are realised with relays, static processing devices and micro-computers.

The tasks of protective systems include sensing abnormal condition, annunciation of abnormal condition alarm, automatic tripping, back-up protection protective signalling etc.

The tasks of control and monitoring system in a substation include data collection, scanning event reporting and recording; voltage control, power control, frequency control, other automatic and semi-automatic control etc.

The two systems work in close co-operation.

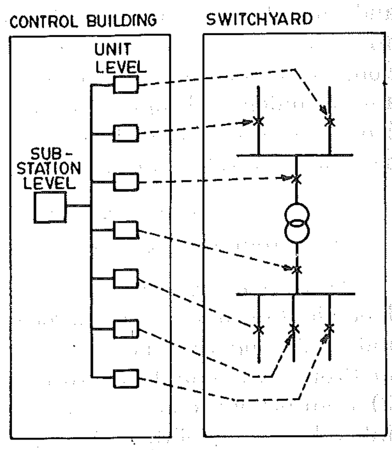
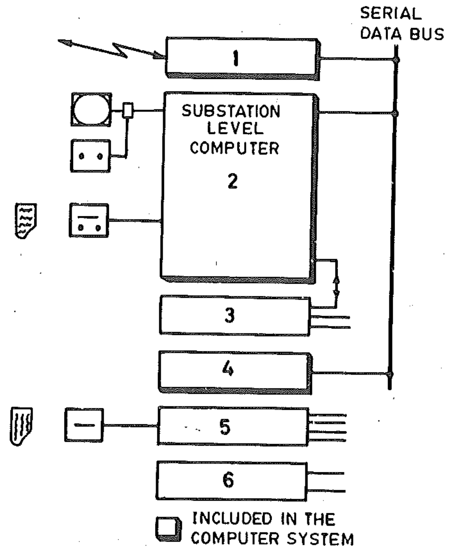


Fig. 43.41. Configuration of protection and control in a substation in two levels.
1. Substation Level 2. Unit Level

43.42. TWO HIERARCHICAL LEVELS IN A SUBSTATION

Two protection and control equipment mentioned above are generally arranged it two hierarchical levels. *From the higher (substation) level, the entire substation is controlled and supervised. From the lower (unit) level, the lines, transformers etc. are controlled and supervised. The equipment on unit level is divided into a number of independent units, each controlling one unit.* This division improves the operating reliability and simplifies future extensions such as additional lines.

1. Upper level (substation control level)
2. Unit level (Equipment level Transformer, line, busbar, reactor etc.) Also included are,
3. Inter level communication
4. Man-machine interface
5. Interface with load control centre.



1. Remote control adaption
2. Man machine communication, supervision, (Automatic control)
3. Synchronising equipment
4. General Unit
5. Disturbance recorder
6. Busbar protection

Fig. 43.42. Functions in substation level.
(Most functions are stored in substation level computer.)

43.43. SUBSTATION LEVEL (UPPER LEVEL)

The following main functions are arranged in substation level. Automatic functions, supervisory functions. Man-machine communication, Busbar protection.

(*i*) Ordinary man-machine communication system of the substation.

(*ii*) Remote control inter-face.

(*iii*) Synchronising

(*iv*) Disconnector Inter-locking

(*v*) Busbar Protection (Relay Protection) System

(*vi*) Fault annunciation

(*vii*) Automatic Network restoration

(*viii*) Automatic Switching sequences

(*ix*) Load Shedding/Load re-connection

(*x*) Voltage control

(*xi*) Compiling of energy and other reports

(*xii*) Disturbance recording

(*xiii*) Sequential events recording.

Most of these functions are integrated as softwares in the sub-station level computer. This software is of modular-design, which facilitates addition of new functions. Table 43.8 gives the categorywise classification.

Table 43.8
Classification of Function at Substation Level (Upper Level)

Protection	Busbar protection
Automatic functions	Synchronising voltage regulation load, switching, power system restoration sequential operations etc.
Supervision	Fault annunciation, sequential events recording disturbance recording, energy reports, self supervision of the electronic system, fault statistics.
Man-machine Communication.	Operations and indications, interlocking of disconnectors adaption to remote control facilities etc.

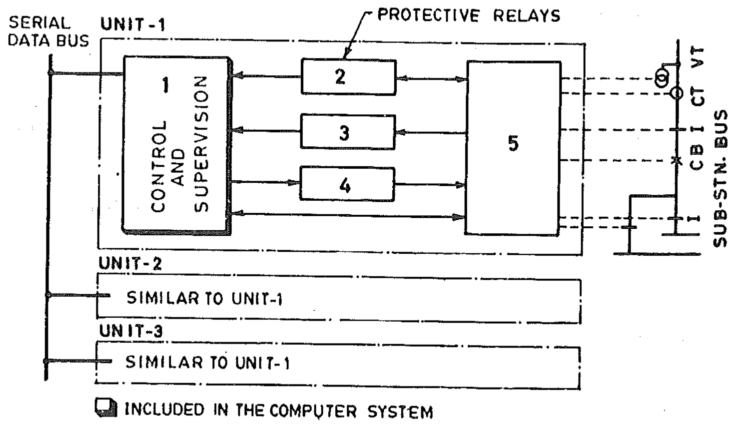


Fig. 43.43. Line Unit Level. Functions stored in programs of unit level microcomputer.

1. Unit level microcomputer, control, supervision of circuit breakers, disconnectors, time-tagging events auto-reclosing etc.
2. Protective Relays 3. Energy Metering 4. Synchronising checks 5. Switchgear Interface

Most of the functions are stored in the substation level computer in the form of software. The software is modularised to facilitate the incorporation of new functions and to simplify future extension of the station. Because of the considerable amount of data to be processed disturbances are registered in a separate unit.

43.43.1. Unit Level

The entire substation is divided into certain 'Units' (Similar to protective zones) which include one or two major equipment such as line, sub-bar section, transformer, etc.

The functions relating to particular unit include the following :

— Line Protection, Breaker Failure Protection, etc.
— Auto reclosing
— Synchronising check
— Energy metering
— Acquisition and time tagging of events
— Acquisition of position indication and measured values
— Execution of commands from substation-level computer
— Back-up control.

Table 43.9 gives categorywise classification.

Table 43.9
Classification of functions of Unit Level

Protection	Line protection, transformer protection, breaker-failure protection, reactor protection etc.
Automation	Auto-reclosing, synchronising checks.
Supervision	Supervision of position of Circuit-breakers, disconnectors, recording of events, energy metering, self-supervision of electronic system fault location on line etc.
Inteface	Switchgear interface, electronic system interface.

Functions which refer to a particular unit are located at unit level. Units are mostly independent of each other. Fault occurring in one unit does not influence other unit control and protection Equipment for each unit is located in a cubicle for that unit.

43.43.2. Inter-level Communication

Information is transferred between the two control levels primarily *via* a serial data bus, where the substation level computer controls the traffic by cyclic boiling the other units connected to the bus. The substation oriented acquisition signals and the serial transmission of information, between the control levels reduces the amount of cabling and terminal blocks.

Table 43.10
Automatic Control Functions in Substations

Auto-reclosing	Single phase or three phase auto-reclosing of line circuit-breakers.
Automatic Synchronising	Check phase sequence, frequency, voltage levels Coincidence of phase voltages and close the circuit-breaker.
Automatic Voltage regulation	Regulate bus voltage by tap-changing and shunt compensation.
Automatic Power restoration	Make attempt for restoration after unsuccessful autoreclosing and after substation blackout.
Sequential operations	Predetermined switching sequences *e.g.* load transfer from one bus to another.
Load shedding	To shed predetermined load when frequency falls. Check for voltage rise.

Table 43.11
Protective function in a substation

1. Detection of fault at the earliest
2. Prevent or minimise damage
3. Disconnect faulty line
4. Detect phase to phase faults and phase to ground fault
5. Overloading protection
6. Overheating prevention
7. Overcurrents prevention
8. Abnormal voltage prevention.

Requirements of Protection and Control Equipment in Substations

The various protection and control functions in a substation have to fulfil certain requirements originating from the power system and the high voltage equipment in the station but they also must fulfil network operation and stability requirements. From the protection and control architecture point of view these main requirements are :

1. **Dependability.** The dependability of a function is the probability that the function will be executed correctly when wanted.

2. **Security.** The security of a function is the probability that the function will not be performed when unwanted.
3. **Degradation withstand capability.** Degradation is the percentage of individual functions that will be inoperative by a single failure in the protection and control system.
4. **Back up Protection.** Principally, the fault clearing ability can not be allowed to be lost. The required degree of dependability in the fault clearing function can be met only with back-up functions. These can be of two types; remote or local.

Remote back-up functions will of then be necessary 'locally' in a station. The transformer overcurrent protection is often the back-up for the line protection in case of line fault. The totally performed remote back-up requires a separation of the two functions, so that both are not lost simultaneously at a single fault in the protection of control equipment.

43.44. FUNCTIONS PERFORMED BY PROTECTION AND CONTROL EQUIPMENT

The different functions performed by the protection and control equipment in a substation or power station have to be grouped for analysis of the architecture. This grouping of the different functions is not associated directly with a physical separation of the equipment and the function groups will be used only to identify factors that influence the realization of the structure.

The function groups below are used in a typical architecture :

(*i*) Fault clearing functions sub 1

(*ii*) Fault clearing functions sub 2

(*iii*) Emergency control functions

(*iv*) Non-emergency control functions

(*v*) Acquisition of information for analysis

(*vi*) Man/machine communication for service and maintenance.

The function group above are defined as strict groups of functions. Thus, the group will include all components to perform the function. A specific component can be associated with more one group. For the following discussion we have to strictly associate the groups with functions and level out aspects concerning realization and component specification.

An abnormal condition will, after a time develop into a main component fault if no preventive measure is taken. This preventive measure can either restore normal operation or result in a safe status where a part of the system is out of operation.

The fault clearing will separate the faulty part from the system and thus change the status from power system fault condition to a safe condition. The required function for a specific type of station will not be discussed, only their association with the function groups.

Fault clearing functions sub 1

Fault clearing functions sub 2

The fault clearing function include all functions for automatic fault clearing power system faults in the group clearing of line and power system apparatus faults as well as network protection. The group 'fault clearing' include basically the function performed by the protection equipment. The fault clearing functions have to be divided into two groups in cases of redundant (duplicated) protections, which are completely separated. These groups are designated 'Fault clearing function sub 1' and 'Fault clearing function sub 2'.

Emergency control functions

This group includes the functions that manually of automatically perform actions to prevent abnormal power system conditions from developing into a main component fault. The group includes protection, alarm, metering and other functions to detect abnormal conditions as well as manual and automatic control to perform the preventive measures. In case of remotely controlled stations, naturally, a part of the remote control equipment can be associated to this group.

Non Emergency Control functions

This group includes all functions for operation during non-system faults and safe status conditions. Both manual and automatic functions are included for the optimization of operation, voltage and frequency control changing at operation mode as well as other functions related to the non-disturbed operation of the network and station. In this group, manual and automatic functions for restoration of the operation after a disturbance are also included.

Acquisition of information for analysis.

This group contains functions for acquisition, storage, transmission and presentation of information to enable the analysis of network and equipment performance and behaviour both during non-system and system fault conditions. Energy management and measuring functions are also included.

Man/machine communication for service and maintenance.

This group includes the functions that enable supervision testing maintenance of the protection and control equipment as well as functions for the modification of control and protection function and setting values.

43.45. PROTECTION AND CONTROL CONFIGURATION

Integrated or modularized (decentralised) systems

Regardless of the high voltage scheme of a substation, the station can be divided into a number of separately controllable units such as line feeders transformers, busbars operated breakers and isolators. The normal protection and control structure practice is to establish two hierarchical levels for the protection, supervision and control to be provided in a substation.

Integrated equipment (centralised)

Measuring data from distributed measuring transducers are brought to a central computers *via* high-speed communication links. The central computer can perform integrated relaying and control functions.

Modularized equipment (decentralized of Centralized)

Protection and control devices, in principle according to current practice. However with increased capability of information transfer *via* the communication system. With a modularized approach a hierarchy with a unit level and station level is normally adopted.

Unit level

The unit level is related to each unit such as a line transformer, busbar, etc and is at present mainly attributed to protection functions. The protection devices are modularized and normally placed so that they can be physically identified as belonging to a specific unit.

Station level

The control functions, either manual or automatic normally handle functions that concern the overall operation of the substation and handle the communication with remote control centres.

There are functions which can not be clearly allocated to unit or station level, depending on the system design, type of equipment, functional requirements, etc. In practice some of the functions will contain a less well defined structure with a combination of unit and station level functions.

When taking the basic requirements into account, with reference to the required degree of dependability, security and degradation, a modularized approach is advantageous. The consequence of communication speed requirements and interference withstand capability should also naturally be modularized approach to decrease the information flow with the station and to isolate more sensitive equipment further back in the control system from interference. All functions that can be performed at unit level should be kept at this level.