**ADVANCED ADIABATIC COMPRESSED AIR ENERGY STORAGE**

Mukesh Gonde1, Rohit Prakash2, S.R. Gawande3

[1mukesh.gonde@gmail.com](mailto:1mukesh.gonde@gmail.com), [2prakashrohit93@gmail.com](mailto:2prakashrohit93@gmail.com)

Department of Electrical Engineering, KDKCE, Nagpur

**ABSTRACT**

A novel adiabatic compressed air energy storage and electricitygeneration using compressed air energy is proposed. It captures Excess power prior to electricity generation so that electrical components can be downsized for demand instead of supply. Large scale penetration of renewable energies such as wind and solar into the electric grid is complicated by their intermittency. Energy storage systems can mitigate these fluctuations by storing off-peak energy for use at peak-demand times. Compressed air energy storage (CAES) is one of the most promising storage technologies due to the large amount of energy that can be stored at an economical cost. This paper shows the transformation of photovoltaic (PV) electricity production from an intermittent into a dispatchable source of electricity by coupling PV plants to compressed air energy storage (CAES) gas turbine power plants.

KEY WORDS: CAES, Adiabatic air storage

1. INTRODUCTION

Renewable energy such as wind and solar energy are clean and available as long as the wind blows or sunshines. Two main disadvantages of these energy sources are their intermittency and that their availabilities do not often correspond to power demand. For example, wind energy tends to be more abundant at night when powerdemand is low. Variations in wind speed and solar intensity make integrating wind and solar energy into the electricpower grid a challenge. An energy storage system can provide steady and predictable power by storing excess energy and releasing it when the demand is greater than supply.

Compressed air energy storage (CAES) is one of the most promising storage technologies due to the large amount of energy that can be stored at an economical cost.[1]Among various energy storage technologies developed in the past few decades, Compressed Air Energy Storage (CAES) has been of special interest for large scale storage of wind energy. CAES systems are usually considered for storage requirements of 10s of MW of electric power and hours of discharge time.[2]Compressed air energy storage (CAES)plants have been in service to store excess off-peak electricity in the form of compressed air for use during peak load times. The original idea for CAES power plants was to utilize inexpensive, off-peak electricity to pressurize air at CAES plants, and to store the compressed air in underground reservoirs.[3] During a peak hours of electricity demand, compressed air is heated (to prevent it from freezing during expansion) and expanded in modified gas turbine to generate electricity. The Compressor/expander used to store and extract energy operates nearly so that it is efficient. A variable hydraulic drive, instead of mechanical gearbox, is used for power transmission. This improves the reliability of the transmission system and allows the generator and the storage system to be housed down tower, thus reducing constructionand repair costs. In addition, a cost effective fixed speed inductor generator can be used instead of the combination of a permanent magnet synchronous motor and power electronics for frequency conversion.[4] The first CAES plant was commissioned in Huntorf, Germany in 1978 to provide black-start services to nuclear plants as well as provide relatively inexpensive peak power . The Huntorf plant, which is still in operation, stores up to 310,000 m3 of compressed air at a pressure range of 44–70 bar in two salt caverns and canproduce up to 290MW of electricity at full capacity for 4 h at an air discharge flow rate of 417 kg/s. The second utility scale CAES plant was commissioned in 1991 in McIntosh, Alabama and is still in operation as well. The McIntosh plant can generate 110MW of electricity at full capacity for 26 h at an air discharge rate of 154 kg/s. It stores up to540,000 m3 of compressed air at a pressure range of 45–74 bar in a salt cavern [1,5]. The Alabama plant consumes up to 25% less natural gas than the Huntorf plant as waste heat from the exhaust of the low pressure expander is recuperated to preheat discharge air from the cavern prior to entering the high pressure combustor.

Normal compressed air energy storage power plants function in similar manner to conventional gas turbine peak-load power plants, with one decisive difference: the gas turbine in conventional power plants require up to two third of mechanical energy which they generate, to drive their compressors. Only about one third is available as operating power for the electricity generators. This is not the case with compressed air energy storage power plants: here, the pre-compressed air and combustion gases are channeled directly to combustion chamber. Correspondingly higher turbine outputs can be transferred to the generator shafts.

At the core of CAES power plants, is large compressed air store, which is charged by means of electrically driven compressors during low load periods when availability is high. As well as aquifers and porous rock formation, large carven in underground salt carven (which can be created by solution mining) are most suitable. The technology is proven and tested. It has long been practice to use salt domes for stockpiling of natural gas reserves. And there are also two instances where these domes are used in CAES plants. An ‘Adiabatic’ storage power plant (AA-CAES) are able to operate without any fossil fuel, and requires about 1.4 KWh of low electricity to generate 1 KWh of peak-load electricity.

Fig1.1General working of AA-CAES plant

1. TYPES OF AIR STORAGE

Compression air generates heat; the air is warmer after compression. Expansion requires heat. If no extra heat is added, the air will be much colder after expansion. If the heat generated during compression can be stored and used during expansion, the efficiency of the storage improves considerably. There are three ways in which a CAES system can deal with the heat. Air storage can be adiabatic, diabatic, or isothermal

* 1. ADIABATIC

Adiabatic storage retains the heat produced by compression and returns it to the air when the air is expanded to generate power. This is a subject of ongoing study, with no utility scale plants as of 2010, but a German project ADELE is planned to enter development in 2013. The theoretical efficiency of adiabatic storage approaches 100% with perfect insulation, but in practice round trip efficiency is expected to be 70%. Heat can be stored in a solid such as concrete or stone, or more likely in a fluid such as hot oil (up to 300 °C) or molten salt solutions (600 °C).stored heat, during later discharge, re-used to pre-heatthe compressed air. The heatstorage facilities are up to 40-mhigh containers with beds of stones orceramic moulded bricksthrough which the hot air flows.

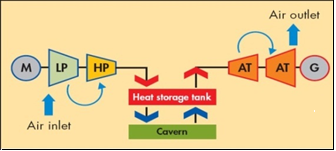


Fig2.1, Adiabatic storage power plants

* 1. DIABATIC

Diabatic storage dissipates much of the heat of compression with intercoolers (thus approaching isothermal compression) into the atmosphere as waste; essentially wasting, thereby, the renewable energy used to perform the work of compression. Upon removal from storage, the temperature of this compressed air is the one indicator of the amount of stored energy that remains in this air. Consequently, if the air temperature is low for the energy recovery process, the air must be substantially re-heated prior to expansion in the turbine to power a generator. This reheating can be accomplished with a natural gas fired burner for utility grade storage or with a heated metal mass. As recovery is often most needed when renewable sources are quiescent, fuel must be burned to make up for the *wasted* heat. This degrades the efficiency of the storage-recovery cycle; and while this approach is relatively simple, the burning of fuel adds to the cost of the recovered electrical energy and compromises the ecological benefits associated with most renewable energy sources. Nevertheless, this is thus far the only system which has been implemented commercially.

* 1. ISOTHERMAL

Isothermal compression and expansion approaches attempt to maintain operating temperature by constant heat exchange to the environment. They are only practical for low power levels, without very effective heat exchanger. The theoretical efficiency of isothermal energy storage approaches 100% for perfect heat transfer to the environment. In practice neither of these perfect thermodynamic cycles are obtainable, as some heat losses are unavoidable.

* 1. OTHER

One implementation of isothermal CAES, uses high, medium and low pressure pistons in series, with each stage followed by an airblastventuri pump that draws ambient air over an air-to-air (or air-to-seawater) heat exchanger between each expansion stage. Early compressed air torpedo designs used a similar approach, substituting seawater for air. The venturi warms the exhaust of the preceding stage and admits this preheated air to the following stage. This approach was widely adopted invarious compressed air vehicles such as H.K. Portesinc's mining locomotive sand trams. Here the heat of compression is effectively stored in the atmosphere (or sea) and returned later on.

1. COMPRESSORS AND EXPANDERS

Compression can be done with electrically powered turbo compressors and expansion with turbo 'expanders' or air engines driving electrical generators to produce electricity. The electrically driven compressor are able to compress the air in the air storage tank or carven up to the pressure of 160 bar and are able to cope up with the temperature rise of 600o C.

1. STORAGE

The storage vessel is often an underground cavern created by solution mining(salt is dissolved in water for extraction) or by utilizing an abandoned mine; use of porous rock formations such as those in which reservoirs of natural gas are found has also been studied. Plants operate on a daily cycle, charging at night and discharging during the day. Compressed air energy storage can also be employed on a smaller scale such as exploited by air cars and air-driven locomotives, and also by the use of high-strength carbon fiber air storage tanks. However, when compressed air is stored at room temperature this stored air, in general, contains the same amount of energy per pound as uncompressed room temperature air. The considerable amount of energy used to compress this air is not stored there if the air is allowed to reduce to room temperature. Therefore, to obtain substantial energy from the expansion of this stored room temperature compressed air a heat reservoir must be provided to supply the needed energy. This can be challenging in mobile applications.

1. CAES PLANTS IN EXISTANCE TODAY

Two commercial CAES power plants are currently operating—the 290MW Huntorf, Germany plant commissioned in 1978 and the 110MW McIntosh, Alabama plant commissioned in 1991. Both plants are peak electricity production plants and have proved reliable.

Table5.1 Commercially working CAES plants

|  |  |  |
| --- | --- | --- |
| Location | HUNTORF, GERMANY | Mclntosh, USA |
| COMISSIONED | 1978 | 1991 |
| OUTPUT | 290 MW over 2hrs | 110 MW over 26 hrs |
| ENERGY REQUIRED FOR 1KWh EL | 0.8 KWh electricity1.6 KWh gas | 0.69 kWh electricity  1.17 KWh gas |
| PRESSURE TOLERANCE | 50 - 70 bar | 45 - 76 bar |
| STORE | Two cylindrical salt caverns, each with 150000 m3 a depth of 600 m-800 m ( height 200 m, diameter 30 m) | Salt cavern, 538000 m3 at a depth of 450 m-750 m |
| REMARK | World’s first CAES plant | First CAES plant with recuperator |

1. ADIBATIC PROCESS

An adiabatic process  is a process that occurs without the transfer of heat or matter between a system and its surroundings.A key concept in thermodynamics, adiabatic transfer provides a rigorous conceptual basis for the theory used to expound the first law of thermodynamics. It is also key in a practical sense, that many rapid chemical and physical processes are described using the adiabatic approximation; such processes are usually followed or preceded by events that do involve heat transfer. Adiabatic processes are primarily and exactly defined for a system contained by walls that are completely thermally insulating and impermeable to matter; such walls are said to be adiabatic. An adiabatic transfer is a transfer of energy as work across an adiabatic wall or sector of a boundary. Approximately, a transfer may be regarded as adiabatic if it happens in an extremely short time, so that there is no opportunity for significant heat exchange An adiabatic transfer of energy as work may be described by the notation *Q* = 0 where *Q* is the quantity of energy transferred as heat across the adiabatic boundary or wall. An ideal or fictive adiabatic transfer of energy as work that occurs without friction or viscousdissipation within the system is said to be isentropic with Δ*S* = 0.For a natural process of transfer of energy as heat, driven by a finite temperature difference, entropy is both transferred with the heat and generated within the system. Such a process is in general neither adiabatic nor isentropic, having *Q* ≠ 0 and Δ*S* ≠ 0.

For a general fictive quasi-static transfer of energy as heat, driven by an ideally infinitesimal temperature difference, the second law of thermodynamics  provides that δ*Q* = *T* de*S*, whereδ*Q* denotes an infinitesimal element of transfer of energy as heat into the system from its surroundings, *T* denotes the practically common temperature of system and surroundings at which the transfer takes place, and de*S* denotes the infinitesimal element of entropy transferred into the system from the surroundings with the heat transfer. For an adiabatic fictive quasi-static process, δ*Q* = 0 and de*S* = 0.For a natural process of transfer of energy as heat, driven by a finite temperature difference, there is generation of entropy within the system, in addition to entropy that is transferred into the system from the surroundings. If the process is fairly slow, so that it can be described near enough by differentials, the second law of thermodynamics observes that δ*Q* < *T* d*S*. Here*T* denotes the temperature of the system to which heat is transferred. Entropy di*S* is thereby generated internally within the system, in addition to the entropy de*S* transferred with the heat. Thus the total entropy increment within the system is given by d*S* = di*S* + de*S.*A natural adiabatic process is irreversible and is not isentropic. Adiabatic transfer of energy as work can be analyzed into two extreme component kinds. One extreme kind is without friction or viscous dissipation within the system, and this is usually pressure-volume work, denoted customarily by *P* d*V*. This is an ideal case that does not exactly occur in nature. It may be regarded as "reversible". The other extreme kind is isochoric work, for which d*V* = 0, solely through friction or viscous dissipation within the system. Isochoric work is irreversible. The second law of thermodynamics observes that a natural process of transfer of energy as work, exactly considered, always consists at least of isochoric work and often of both of these extreme kinds of work. Every natural process, exactly considered, is irreversible, however slight may be the friction or viscosity.

* 1. ADIABATIC HEATING

Adiabatic changes in temperature occur due to changes in pressure of a gas while not adding or subtracting any heat. In contrast,free expansion is an isothermal process for an ideal gas.Adiabatic heat occurs when the pressure of a gas is increased from work done on it by its surroundings, e.g., a piston compressing a gas contained within an adiabatic cylinder. This finds practical application in Diesel which rely on the lack of quick heat dissipation during their compression stroke to elevate the fuel vapor temperature sufficiently to ignite it.Adiabatic heating also occurs in the Earth's atmosphere when an air mass descends, for example, in a katabatic wind or [Foehn](http://en.wikipedia.org/wiki/Foehn_wind" \o "Foehn wind) or chinook wind flowing downhill over a mountain range. When a parcel of air descends, the pressure on the parcel increases. Due to this increase in pressure, the parcel's volume decreases and its temperature increases, thus increasing the internal energy.

The mathematical equation for an ideal gas undergoing a reversible (i.e., no entropy generation) adiabatic process is



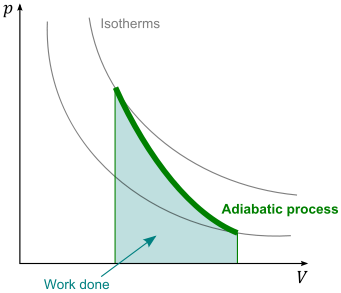
Constant …(6.1.1)

where *P* is pressure, *V* is volume, and

…(6.1.2)



Fig6.1 Adiabatic process

[](http://en.wikipedia.org/wiki/File:Adiabatic.svg)

 C_{P}  being the specific heat for constant pressure, C_{V}  beingthe specific heat for constant volume,  \gamma  is the adiabaticindex, and  f  is the number of degrees of freedom (3 for monatomic gas, 5 for diatomic gas and collinear molecules e.g. carbon dioxide).

For a monatomic ideal gas,  \gamma = 5/3 \,, and for a diatomic gas (such as nitrogen and oxygen,the main components of[air](http://en.wikipedia.org/wiki/Earth%27s_atmosphere))  \gamma = 7/5 \,.Note that the above formula is only applicable to classical ideal gases and not Bose–Einstein orFermi gases.For reversible adiabatic processes, it is also true that



Constant …(6.1.3)



Constant …(6.1.4)

where *T* is an absolute temperature.This can also be written as



Constant …(6.1.5)

* 1. EXAMPLE OF ADIABATIC COMPRESSION

Let's now look at a common example of adiabatic compression- the compression stroke in a gasoline engine. We will make a few simplifying assumptions: that the uncompressed volume of the cylinder is 1000cc's (one liter), that the gas within is nearly pure nitrogen (thus a diatomic gas with five degrees of freedom and so \gamma  = 7/5), and that the compression ratio of the engine is 10:1 (that is, the 1000 cc volume of uncompressed gas will compress down to 100 cc when the piston goesfrom bottom to top). The uncompressed gas is at approximately room temperature and pressure (a warm room temperature of ~27 degC or 300 K, and a pressure of 1 bar ~ 100,000 Pa, or about 14.7 PSI, or typical sea-level atmospheric pressure).



Constant



so our adiabatic constant for this experiment is about 1.58 billion. The gas is now compressed to a 100cc volume (we will assume this happens quickly enough that no heat can enter or leave the gas). The new volume is 100 ccs, but the constant for this experiment is still 1.58 billion:



Constant =

so solving for P:



P

or about 362 PSI or 24.5 atm. Note that this pressure increase is more than a simple 10:1 compression ratio would indicate; this is because the gas is not only compressed, but the work done to compress the gas has also heated the gas and the hotter gas will have a greater pressure even if the volume had not changed.

We can solve for the temperature of the compressed gas in the engine cylinder as well, using the ideal gas law. Our initial conditions are 100,000 pa of pressure, 1000 cc volume, and 300 K of temperature, so our experimental constant is:



Constant =

We know the compressed gas has V = 100 cc and P = 2.50×106pascals, so we can solve for temperature by simple algebra:

 {P V \over {\operatorname{constant}}} = T = {{2.50 \times 10^6 * 100} \over {3.33 \times 10^5}} = 751 

That's a final temperature of 751 K, or 477 °C, or 892 °F, well above the ignition point of many fuels. This is why a high compression engine requires fuels specially formulated to not self-ignite (which would cause engine knocking when operated under these conditions of temperature and pressure), or that a supercharger and inter cooler to provide a lower temperature at the same pressure would be advantageous. A diesel engine operates under even more extreme conditions, with compression ratios of 20:1 or more being typical, in order to provide a very high gas temperature which ensures immediate ignition of injected fuel

* 1. ADIABATIC EXPANSION OF GAS

For an adiabatic free expansion of an ideal gas, the gas is contained in an insulated container and then allowed to expand in a vacuum. Because there is no external pressure for the gas to expand against, the work done by or on the system is zero. Since this process does not involve any heat transfer or work, the First Law of Thermodynamics then implies that the net internal energy change of the system is zero. For an ideal gas, the temperature remains constant because the internal energy only depends on temperature in that case. Since at constant temperature, the entropy is proportional to the volume, the entropy increases in this case, therefore this process is irreversible

1. ADIABATIC STORAGE OBJECTIVE

Adiabatic storage power plants store not only the compressed air, but also the heat which is released upon compression of the air. For generation of electricity, the heat is returned to the compressed air which flows to turbine. This renders the use of natural gas unnecessary. Operated with only regenerative electricity, Adiabatic CAES plant should achieve the efficiency up to 70%. The development of such plants is supported by the European Union, but still in its infancy. A demonstration power plant could be built in five to 10 years. Until then, there are numerous challenges to overcome.

**Heat storage tank**with storage capacity of up to 1200 MWh at temperature over 600 oC are required. Two lines of development are investigated

1. Solid stores made up of ceramic, natural stones, concrete or cast iron, could be directly charged and discharged. They have proven themselves in industry, are simple in structure, and have large heat transfer surface. However, solid stores require a pressure-resistant shell.
2. Another technology, also proven many times in industry, uses commercially available fluids. Charging and discharging occur via heat exchanger, so corresponding temperature losses are incurred. But on the other hand, low cost containers can be used.

**Compressors** for charging the store should cope with temperature of up to 600 oC, and generate pressure of up to 160 bar. Other requirementsare; high efficiency, a variable flow rate, and rapid availability with startup time of few minutes

**Air turbine** must be newly developed, to achieve capacities up to 300 MW by expansion of the compressed hot air to atmospheric pressure, Here, the challenges include: high power density, high entry temperature, large volume flows, simultaneously, high efficiency should be achieved across the entire load range, with low specific cost.

1. CONCLUSION

The flexibility of CAES power plants is similar to that of pumped storage power plants. Full capacity is available just few minutes after start-up. For limited periods, the compressed air stores cover the short term reserve requirement, the minutes reserve, and the balancing capacity, which are needed due to the inexactness of forecast regarding non-conventional power grid –feed. This reduces the need for fossil reserve power plants and additional gird capacity. Non-conventional plants do not need to deactivate in the event of a grid overload, and if there is excess supply of electrical energy, the storage technology refines base-load electricity, converting it to peak-load electricity. Thus, the fluctuating electricity prices on the liberalized electricity market can be used to yield profits. Storage power plants cannot replace the entire requirement for reserve power plants. Within an overall concept, they reduces the amount of grid expansion needed, and shares the task of supplying peak load power with gas power plants, which can be regulated quickly. Grid optimization is complemented to no small extent by more effective consumptionmanagement, with which load fluctuations are regulated not only on the supply side, but also on the demand side.

REFERENCE

[1]Hosseinsafaei, David w. Keith, Ronald J. Hugo, “Compressed Air Energy Storage(CAES) with compressors distributed at heat loads to enable the heat loads to enable waste heat utilization”, journal published on 9 Feb. 2012.

[2] HosseinSafaeiMohomadabadi, Ronald J. Hugo, “Enhancing the economics of wind based compressed air energy storage by waste heat reciovery”.ASME 5th international conference on energy sustainability and 9th fuel cell science, engineering and technology conference, Aug. 2011 Washington D.C. USA.

[3] James Mason, VasilisFthnakis,” coupling of PV and CAES power plant to transform intermittent PV electricity into a dispatchable electricity source” Renewable energy research institute, Farmingdale USA, Feb 2008.

[4]Mohsen SaSadat and Pelly Y Li2,” Modeling and control of a novel compressed air energy storage system of off shore wind turbine,”2012 American conference Fairmont Elizabeth, montreal, Canada, June 27-29, 2012.

[5] Dr. Michael Nakhamkin,”15 MW CAES plant with above ground storage-distributed generation based on novel concept Developed by ESPC”, The CAES technology the 110 MW CAES project Alabama Electric Cooperative.

BOOK:

[6] R.K. Rajput “Thermal engineering” 9TH edition 2011, Laxmi publications Pvt. Ltd., New Delhi 110002, *,[*Page no. 677 to 686]

[7] B.H. Khan, “NONCONVENTIONAL ENERGY RESOURCES”, TATA McGraw-Hill Publishing Company Ltd, New Delhi- 100085.

[8] G.D. RAI, “Non Conventional Energy Resources”, 5th edition April 2011, Khanna publishers, New Delhi 100006,[page no. 779-785. 789-791]