# Supplemental Problems

**Part I: Chapters 1 - 18**

**to accompany the 3rd Edition of**

**Power Electronics: Converters, Applications and Design**

**by**

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# Chapter 1

## S1.1 Linear or switch mode use of semiconductors

Explain the most important differences in the use of semiconductors for linear electronics compared to power electronics.

## S1.2 Increased use of power electronics

Power electronics has existed as a special field for about 40 years. In this period there has been a fast development for systems based on power electronics. Describe the causes of this development.

## S1.3 Applications of power electronics

In Table 1-1, it is listed 7 different applications of power electronics. Characterize these 7 areas with respect to specifications like power rating, dynamics and efficiency.

## S1.4 Multiple converters

(a) Show that the power converter shown in Fig. 1-3 consists of two rectifiers, one inverter, a transformer and two capacitors serving as power storages.

(b) Draw a block diagram for this converter, like Fig. 1-8.

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# Chapter 2

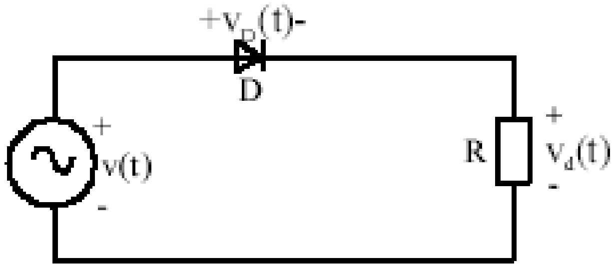
## S2.1 Semiconductor characteristics

(a) Draw the ideal characteristics for
  (I) A diode
  (II) A thyristor

(b) When are the ideal characteristics used, and when are the more complicated characteristics (non-ideal) used?

## S2.2 Basic rectifier

(a) The figure below shows a simple rectifier. Assume the diode to be ideal.




Given: $v(t) = \sqrt{2} \cdot 230 \cdot \sin \omega t$, where $\omega = 2 \pi 50$

(I) Sketch the voltage $v_d(t)$ over the load resistance R, as a function of time. This is the voltage from the rectifier.

(II) Sketch the voltage over the diode D, as a function of time.

(III) Calculate the average value, $V_d$, of the output voltage $v_d(t)$.

(b) Why will a negative temperature coefficient (the on-state voltage falls as temperature increases) make it difficult to parallel connect diodes and thyristors?

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# Chapter 3

## S3.1 Filter

The voltage amplitude is 30 V. Otherwise all data are as in Problem 3-8.

(a) Calculate the average output voltage $V_0$

(b) Assume a large C so that $v_0(t) \approx V_0$
Calculate the load current $I_0$

(c) Calculate the rms value of the inductor current $I_L$.
Show that $I_L^2 = I^2_{avg} + I^2_{rippel}$ . Plot the $v_L(t)$ and $i_L(t)$

(d) The output power is reduced to 80 W. Repeat (b) and (c) above

(e) Find the ratio between rms and average of the inductor current in (c) and (d). Comment the answers.

(f) Plot the current in the capacitor for (c) and (d). Calculate its rms value.

## S3.2 Harmonics

For some common rectifiers, the line current may be like the rms shown in Fig. P3-3a and b (with u = 60$^o$). The need for power pr. phase is the same in the two cases, that is the rms fundamental frequency component of the line currents, are 100A in both cases.

(a) Calculate the amplitude and the rms value for the P3-3 a current.

(b) Calculate the amplitude and the rms value for the P3-3 b current.

(c) Comment the answers above.

## S3.3 Inductor physics

An inductor is made like the one shown in Fig. 3-10 b. The cross sectional core area A = 1 cm$^2$. The air gap is 1 mm. A ferrite which starts to saturate at $B_{sat}$ = 0,3 T is used as the core material. For the non-saturated core assume that the magnetic reluctance of the core can be neglected as compared to that of the air gap. In the first par, the winding has N = 100 turns.

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(a) Calculate the inductance of the inductor.

(b) Calculate the maximum current of the inductor before core saturation.

(c) Electric energy stored in an inductor is $\frac{1}{2}$ L $i^2$. Calculate the maximum stored energy.

(d) Change N to 200, repeat a – c.

(e) Magnetic energy stored in a core air gap is W = $\frac{1}{2}$ BH V for volumes where B and H can be considered constant. Calculate the inductor energy for its maximum current based upon this equation. Compare with the energies calculated based on the inductance and the maximum currents.

## S3.4 Transformer with an air gap in the core

In some applications, there is a need for an air gap in transformer cores. A transformer with its core and primary winding is made like the one shown in Fig. 3-10 b.

The core has a cross sectional area A = 3 $cm^2$.
The air gap is 1 mm.
A ferrite which saturates at $B_{sat}$ = 0.2 T is used as the core material.

For the non-saturated core assume that the magnetic reluctance of the core can be neglected as compared to that of the air gap. The turn number of the primary winding is $N_p$=12.

The primary winding is supplied with a square wave voltage of ± 300V as shown in Fig. P3-8 b with u = π/3 and a frequency of 50 kHz.

(a) Plot the voltage, flux density and magnetizing current waveforms in steady state as functions of time.

(b) Calculate the amplitude of the flux density and the magnetizing current.

(c) Calculate the rms value of the magnetizing current.

(d) A resistive load is connected to the secondary winding. By this the primary current will increase with a current having the same waveform as the primary voltage and amplitude of 20A. Calculate the rms value of this component of the primary current.

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(e) Plot and calculate the rms value of the total primary current.

(f) Repeat (a) – (e) for an air gap of 0.1 mm.

(g) Calculate the lowest frequency where saturation is avoided.

(h) Will this lowest frequency depend on the length of the air gap?

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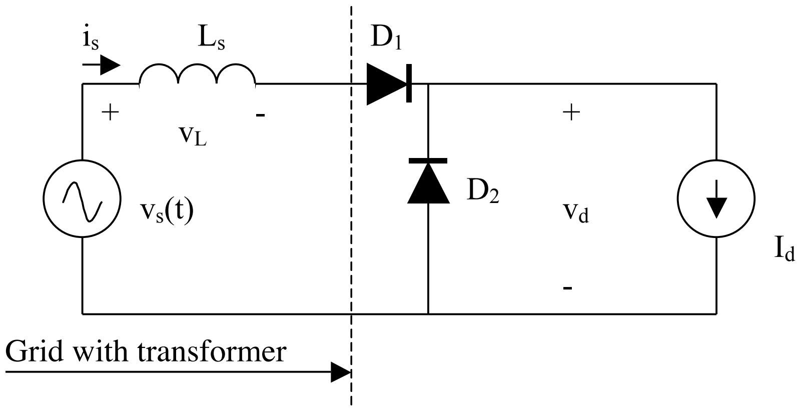
# Chapter 5

## S5.1 Single-phase unidirectional diode circuit.




$V_s = 230$
$L_s = 5mH$
$I_d = 10A$
$f = 50Hz$

In the circuit shown above, the diodes and the current source may be considered ideal.

(a) Sketch the voltages $v_d(t)$ and $v_L(t)$ and the current $i_s(t)$ as a function of time.

(b) Because of the grid inductance $L_s$, there will be a voltage loss in $v_d(t)$ when $v_s(t)$ has a positive zero crossing ($v_s(t)$ goes from negative to positive value). This voltage loss is called commutation voltage loss. Why is there not a similar voltage loss at the negative zero crossing?

(c) Calculate the angle of commutation *u*, the average value of the dc voltage value $V_d$ and power $P_d$.

## S5.2 A single-phase diode rectifier

A single-phase diode rectifier is shown in the figure below. The rms value of the grid voltage is $V_s$ = 230V. Assume an ideal grid ($L_s$=0). Assume that the load is represented by a constant dc current, $I_d$ = 10A. The grid frequency is equal to 50 Hz.

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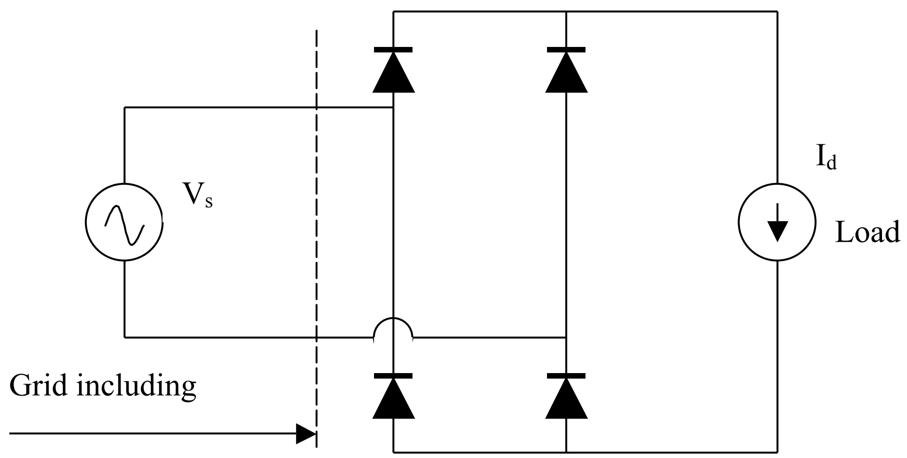


A single-phase diode rectifier with a current source as load.

(a) Sketch the dc voltage $v_d(t)$.

(b) Derive the equation for the average dc voltage.

(c) Sketch $i_s(t)$, and indicate which diodes are conducting as function of time.

(d) Calculate the rms value of the grid current, $I_s$.

(e) Prove that the rms value of the first harmonic of the grid current is given by:

$$I_{s1} = \frac{4}{\sqrt{2}\pi} I_d$$

For odd functions, the Fourier coefficients are given for the h'th harmonic as:

$$a_h = 0 \quad \text{and} \quad b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)d(\omega t)$$

(f) Prove that the power factor PF for this single-phase diode rectifier is 0.9.

(g) Calculate active power, P on the dc side; and P on the ac side.

(h) Why is the apparent power larger than the active power, even when the 1.harmonic current is in phase angle with the grid voltage?

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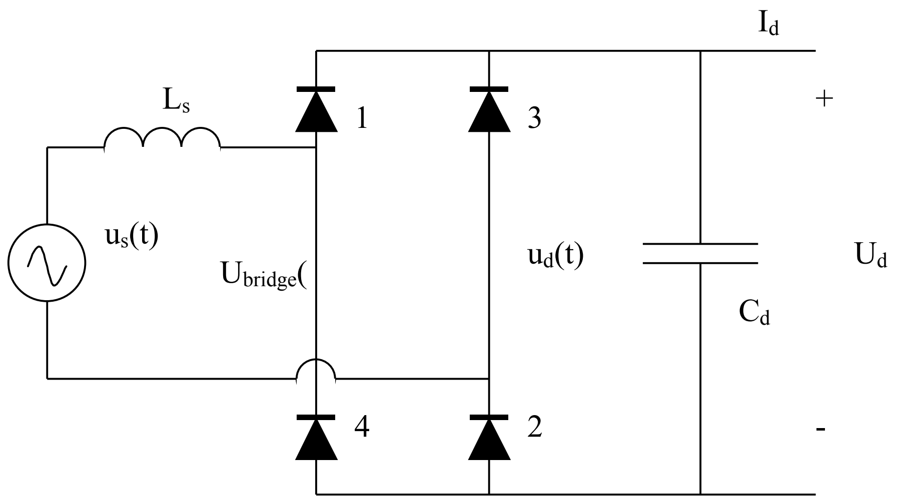
**S5.3 Single-phase diode rectifier with smoothing capacitor.**




The figure shows a single-phase full bridge diode rectifier connected to a smoothing capacitor $C_d$. Assume that the capacitance of the smoothing capacitor is so large that $U_d$ may be considered to be constant (no ripple). The diode rectifier is connected to a grid with a sinusoidal voltage $u_s$, equal to 230 V (rms) with frequency equal to 50 Hz. The inductance of the grid $L_s$ is equal to 1.22 mH.

(a) Calculate the short circuit current of the grid.

(b) The load current $I_d$ (average value) is 10 A. Calculate the power the line is supplying. Use Fig. 5-17.

(c) Calculate the apparent power S supplied by the grid.

(d) The diode rectifier with a large smoothing capacitor is considered to be a load with a bad power factor. Explain why the diode rectifier needs so much apparent power.

(e) Use Fig. 5-18 and 5-19 to find the rms value of the grid current $i_s$, and to find its peak value $\hat{I}_s$.

(f) Sketch the load voltage $v_d(t)$, the voltage of the connection to the grid $v_{bridge}(t)$, the dc current $i_d(t)$ and grid current $i_s(t)$. Also sketch the first harmonic of the grid current $i_{s1}(t)$.

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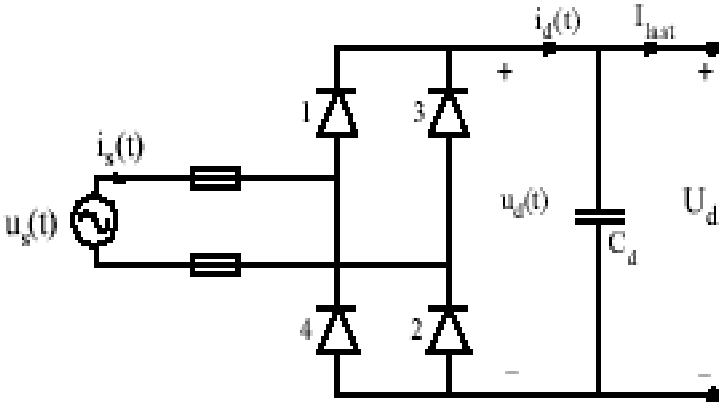
### S5.4 Diode rectifier with fuses




Diode rectifier with fuses

(g) The diode rectifier of the previous problem is protected against over currents by the use of two 16 A fuses in the line connection, as shown in the figure. Will the fuse blow? What could be done to make the 16 A fuses stand the strain?

(h) Would the fuses stand the strain if the same power were delivered to an ohmic load (no rectifier)?

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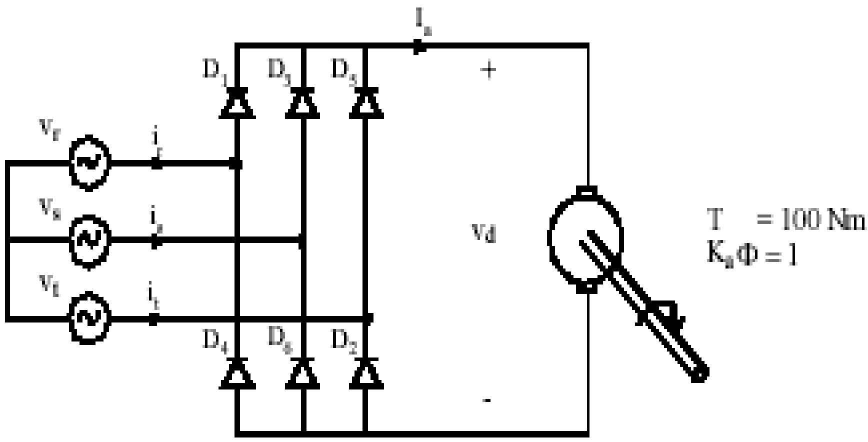
## S5.5 Three-phase diode rectifier.

The diode rectifier shown in the figure below, supplies a DC machine, which has a constant load torque T = 100 Nm. The flux is held constant and $K_a\cdot$□ = 1. This gives an armature current $I_a$ = 100 A. The armature inductance of the machine, $L_a$, is so large that the armature current may be considered to be constant. The line voltage of the grid, $V_{LL}$, is equal to 230V. Assume ideal grid, $L_s$=0.




(a) Sketch the armature voltage $v_d(t)$ and the line currents $i_r(t)$, $i_s(t)$ and $i_t(t)$. Indicate in the sketches when the diodes are conducting.

(b) Calculate the average dc voltage, $V_d$.

(c) Calculate the rms current in phase R, $I_{r,rms}$.

(d) Calculate the rms value of the first harmonic of the phase current, $I_{r1}$.

(e) Prove that for a non-sinusoidal waveform, its rms value is always higher than its rms fundamental value.

(f) List the advantages for a three-phase rectifier compared to a single-phase rectifier?

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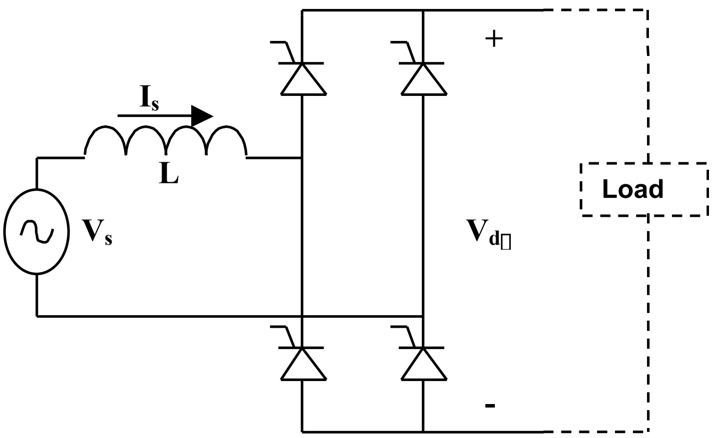
# Chapter 6

## S6.1 Single-phase thyristor converter.

The figure below shows a single-phase thyristor rectifier connected to a 230 V grid. The load is equivalent to a constant dc current of $I_{Load}$ = 10A.

In the first part of problem 6 A, assume L = 0, that is assume instantaneous commutation.




(a) List the conditions that must be fulfilled for making a thyristor conduct? And what are the conditions to make it stop conducting?

(b) Prove that the average voltage $V_{d\alpha}$ at the thyristor rectifier output may be expressed as:

$$V_{d\alpha} = \frac{2\sqrt{2}}{\pi} V_s \cos\alpha \approx 0{,}9 V_s \cos\alpha \,, \qquad \alpha \text{ is the firing angle}$$

(c) For a load voltage of 100 V, find the firing angle $\alpha$.

(d) Sketch $V_{d\alpha}(t)$, $i_s(t)$, and $i_{s,1}(t)$, and indicate which thyristors are conducting, and when they are conducting.

(e) Calculate the rms value, $I_s$, of the ac current $i_s(t)$, and its first harmonic, $i_{s,1}(t)$.

(f) Find the phase angle between $i_{s,1}(t)$ and $v_s$.

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*Given: The Fourier coefficient of an odd function is:*

$$b_n = \frac{2}{\pi}\int_0^{\omega T=\pi} f(\omega t)\sin(n\omega t)\,d\omega t$$

(g) Calculate apparent power, S, and active power, P.

**Now, consider the ac inductance, L =5 mH.**
**The load voltage is still 100V.**

(h) Why is the current commutation no longer instantaneous, for example from thyristor $T_3$ to thyristor $T_1$?

(i) Prove that:

$$V_{d\alpha} = \frac{2\sqrt{2}}{\pi}V_s\cos\alpha - \frac{2}{\pi}X_s I_{Load}$$

(j) And that:

$$2\omega L_s I_{Load} = 2X_s I_{Load} = \sqrt{2}V_s\left(\cos\alpha - \cos\left(\alpha + u\right)\right)$$

where u is the commutation angle.

(k) For the grid inductance L equal to 5 mH, calculate the firing angle, $\alpha$, and the commutation angle, u.

(l) Sketch $V_{d\alpha}(t)$, $i_s(t)$, and $i_{s,1}(t)$. Indicate the firing angle $\alpha$ and the commutation angle u in the sketch.

## S6.2 Three-phase controlled rectifier

A three-phase thyristor converter is shown in the figure below. In the first part of the problem, assume the line inductance to be neglected. The line voltage rms value is 230*V* and 50*Hz* (sinusoidal). The load current is 10*A*.

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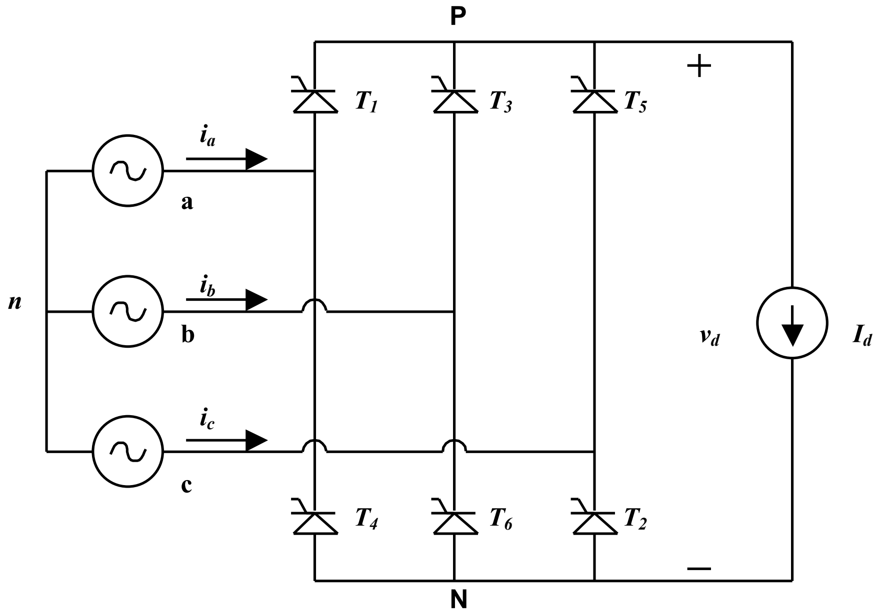


(a) From the figure, it can be seen that $v_d = v_{Pn} - v_{Nn}$. Make a sketch of these three voltages for the case that the gate currents are constantly present.

(b) For the same conditions as in (a), sketch $i_a$, $i_b$, and $i_c$. Indicate in the sketch when the thyristors are conducing.

(c) List the conditions needed for a thyristor to start conducting. What are the conditions for it to stop conducting

(d) Sketch $v_d$, $v_{Pn}$ and $v_{Nn}$ for the firing angle, , equal to 60°.

(e) Find the equation for the average value of the dc voltage $v_d$, where the firing angle  is a variable.

(f) Calculate the ac power passing through the rectifier when the firing angle is 60°

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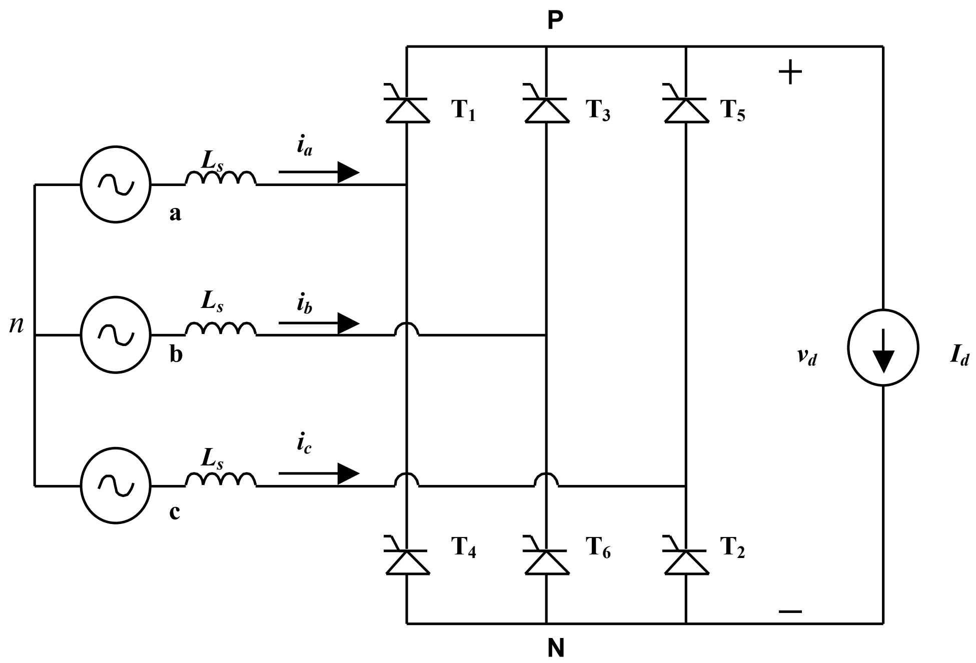
For the rest of the problem, assume $L_s$ = 5*mH*, in all the phases.




(g) Sketch $v_d$, $v_{Pn}$ and $v_{Nn}$ keeping $\alpha$, still equal to 60$^o$.

(h) Find the equation for the average value of the dc voltage $v_d$, where the firing angle $\alpha$ is a variable, taking the influence of the line inductance $L_s$ into the consideration

(i) Calculate the firing angle $\alpha$ that provides the same power as in (f).

(j) Find the commutation angle *u* in this case.

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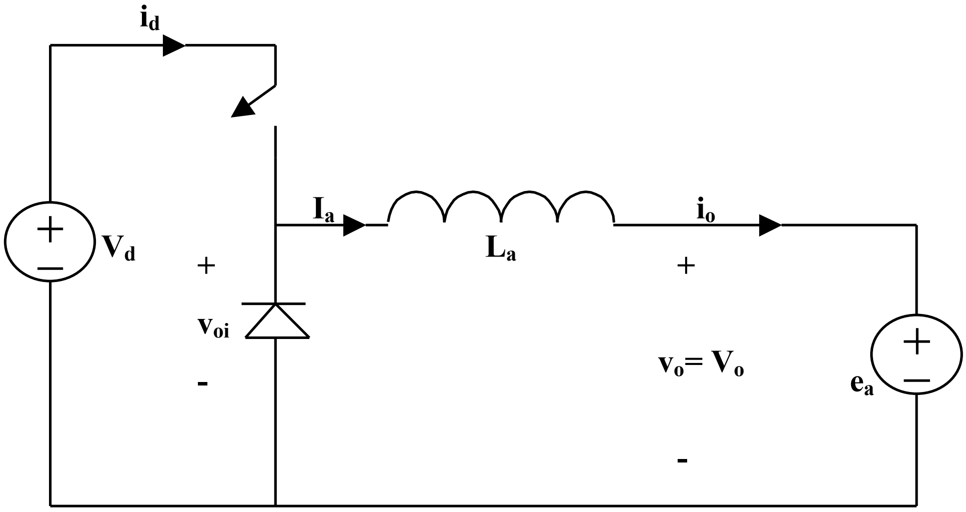
## Chapter 7

### S7.1 Step-down converter

The chopper below controls a dc machine with an armature inductance $L_a$ = 0.2 mH. The armature resistance can be neglected. The armature current is 5 A. $f_s$ = 30 kHz. D = 0.8




(a) The output voltage, $V_o$, equals 200V. Calculate the input voltage, $V_d$.

(b) Find the ripple in the armature current.

(c) Calculate the maximum and the minimum value of the armature current

(d) Sketch the armature current, $i_a(t)$, and the dc current, $i_d(t)$.

(e) The load on the machine is reduced. Calculate $I_a$ when the converter is on the boundary between continuous and discontinuous mode

(f) The load on the dc machine gives $I_a$ = 2A. The current is now discontinuous. What is the back-emf voltage, $E_a$?

(g) Sketch waveforms of (f) similar to Fig. 7-7.

(h) Calculate maximum armature current, $i_{a,max}$

(i) Find $\square_1 T_s$

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## S7.2 Step-down converter characteristics

A step-down dc-dc converter like the one shown in Fig. 7-4a is to be analyzed.

The input voltage $V_d$ = 48 V.
The output filter inductance L = 0.1 mH
Series resistor (with L) R = 0.2 Ω
Assume in all calculations constant voltage over the series resistor R.
The output capacitor C is large; assume no ripple in the output voltage.

Rated output is 20 V and 25 A

(a) Calculate rated output power.

(b) Calculate equivalent load resistance.

(c) Calculate duty ratio D for rated output. The voltage across the series resistor R must be taken into consideration.

(d) Keep this duty ratio constant and increase the load resistance, or reduce the load in W. Find the load current, voltage, watt and the equivalent load resistance $R_B$ at the boundary to discontinuous conduction.

(e) Sketch the inductor current for this operation.

(f) Still keep this duty ratio constant and increase the load resistance, or reduce the load in W until there is only 1 W power to the load. Find the load current, voltage, watt and the equivalent load resistance $R_B$ for this operation.

(g) Sketch the inductor current and the inductor voltage for this operation.

(h) Use the output voltage from (f) and make an accurate calculation of the inductor current. (Do not assume that the voltage over the series resistor R is constant.)

(i) Sketch the inductor current for this accurate calculation.

(j) Compare (g) and (i).

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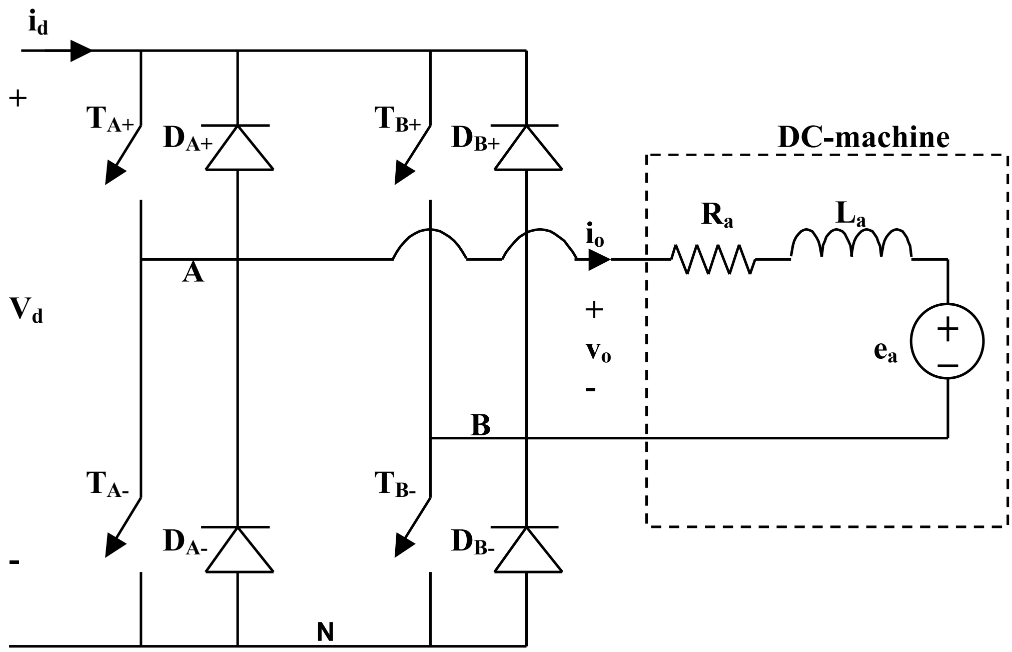
## S7.3 Full bridge DC - DC converter




$V_d$ = 250 V. Switching frequency is 30 kHz. The bridge is connected to a speed controlled dc machine. The armature inductance $L_a$ = 0,2 mH. The armature resistance is negligible.

(a) The bridge may be controlled by the use of unipolar or bipolar PWM. Describe the advantages and disadvantages of these control algorithms.

(b) The bridge is controlled to provide an average output voltage, $V_o$ = 200 V.
Find the duty ratios $D_1$ and $D_2$ and the ripple frequency of the two control principles
Sketch $v_o$(t) for the two control principles.

At a given speed, the back-emf $E_a$ = 200 V. Unipolar PWM is used.

(c) The armature current, $I_a$, is 1 A, find the maximum and the minimum instantaneous armature current. Sketch the armature current, $i_a$(t). Indicate which of the power semiconductors are conducting. Also sketch $i_d$(t).

(d) As in Problem (c), with $I_a$ = 20A.

(e) As in Problem (c), except bipolar PWM is used.

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## S7.4 Step-down converter, discontinuous mode.

In a step-down converter, consider all components to be ideal. The inductance of L is 50 $\mu$H and C is so large that the output voltage can be considered to be constant.

a) For $V_d$ = 40 and $V_o$ = 10V, calculate the duty cycle and the output current when the inductor current is on the edge of the continuous-conduction mode.

b) For output current one tenth of (a), calculate the duty cycle to keep the output voltage constant.

c) Keep the duty cycle from (b). For ± 1% variation in output current, calculate the variation in output voltage.

d) Sketch the characteristic for the duty cycles of (a) and (b).

## S7.5 Step-down converter, cost of the filter inductor

A 1 kW, 48V output step-down converter is to be evaluated. Consider all the components to be ideal. The output capacitor C is so large that the output voltage can be considered to be constant. The input voltage is 100V, and the switching frequency is 80 kHz.

(a) For L = 40 $\mu$H, calculate $I_{L,\,rms}$ and $I_{L,peak}$.

(b) For L= 10 $\mu$H, calculate $I_{L,\,rms}$ and $I_{L,peak}$

(c) Assume that the cost of an inductor varies linearly with the product of $L \cdot I_{L,rms} \cdot I_{L,peak}$
Calculate the ratio of the cost between the inductor of (b) and (a). Compare to the ratio of the inductance.

(d) For L = 2.5 $\mu$H repeat the problems above.

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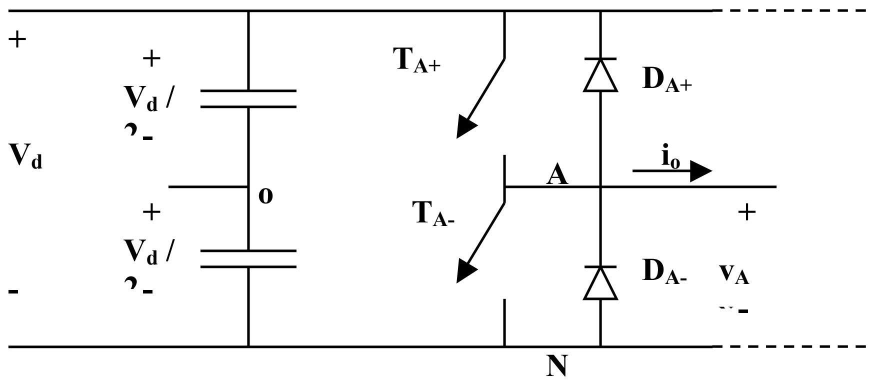
# Chapter 8

## S8.1 Switch-mode inverter (one phase-leg, half bridge)

A general analysis of the switch-mode inverter (shown in the figure below) is to be done. The switching frequency $f_s$, which is also the frequency of the triangular signal is 1450 Hz. The DC voltage, $V_d$, is 600 V. Output voltage is sinusoidal voltage with a frequency equal to 50 Hz. The load is connected between the inverter leg A and the dc voltage midpoint o.




(a) Find the frequency modulation ratio, $m_f$. Why is it chosen as an odd number?

(b) Calculate the output voltage (rms value of 1. harmonic), when the amplitude modulation ratio, $m_a$, is equal to 0.8?

(c) Prove that $(\hat{V}_{Ao})_1$ is $m_a V_d / 2$ .

(d) When $m_a$ varies from 0 to 1, the mo the linear domain. Why?

(e) Compute the rms value of the 5 most dominant harmonics of $v_{Ao}$ (at $m_a$=0,8), by using Table 8-1, page 207. Also indicate the frequencies at which these harmonics appear.

(f) Which frequencies are desirable for the switching frequency? List the advantages and disadvantages of low/high switching frequency.

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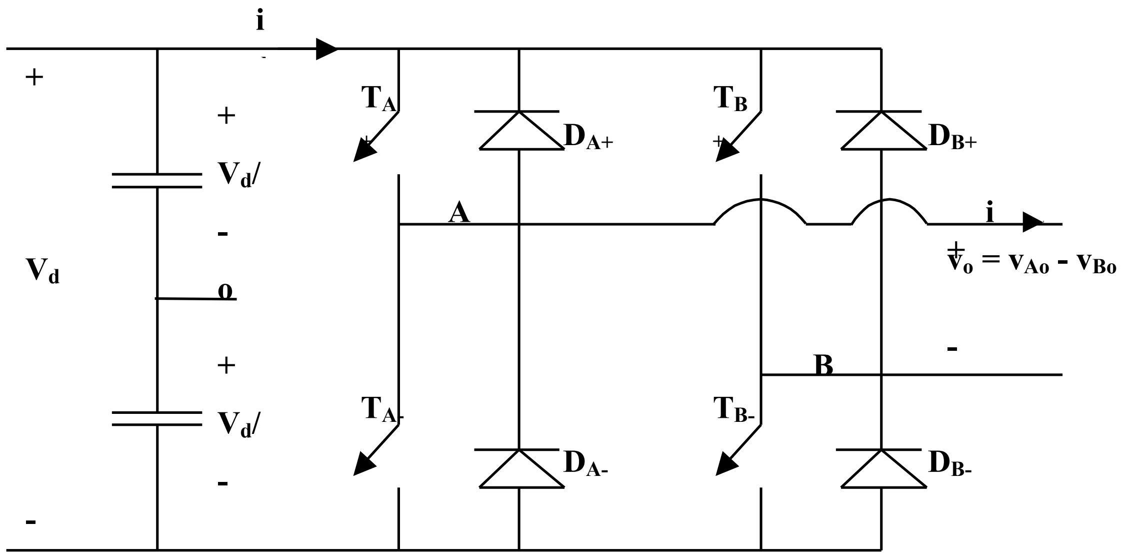
## S8.2 Switch-mode inverter (single phase, full bridge)

The inverter from 8 A is expanded with another leg. It is PWM controlled with bipolar voltage switching. It operates at the same $m_a$ and $m_f$, and $V_d$ still equals 600 V. Output voltage is sinusoidal and has a frequency of 50 Hz.




(a) Why is it advantageous to use full bridge instead of half bridge in case of higher power?

(b) Show that the peak value of the first harmonic component of the output voltage, $\hat{V}_{o1}$, equals $m_a$ times $V_d$ for this inverter.

(c) Why is this type of switching called Bipolar?

(d) Compute the rms value of the 5 most dominant harmonics of $v_{Ao}$ (at $m_a$=0,8), by using Table 8-1, page 207. Also indicate the frequencies at which these harmonics appear.

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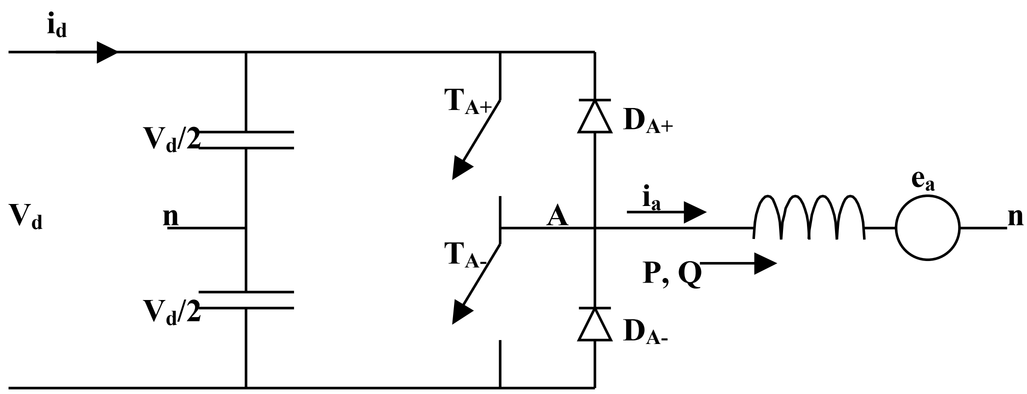
## S8.3 Bipolar single phase half bridge inverter

$L$ = 15 mH

$E_{A1}$ = 230 V

$f$ = 50 Hz

$V_d$ = 800 V




(a) The frequency of the triangular signal is 750 Hz. Calculate the frequency modulation ratio, $m_f$.

(b) Find $m_a$ when the output voltage is 230 V?

(c) Find the angle, $\delta$, between the phasors, $V_A$ and $E_A$ for P = 1 kW and Q = 500 Var.

(d) For the same Q, find $\delta$ and $V_A$ when P = -1 kW (rectifier mode).

(e) Find $\delta$ and $V_A$ for Q = 1 kVar and –1 kVar when P is kept equal to zero.

(f) Sketch the line on which the arrow head of voltage phasor $V_A$ moves along for
P = 0 kW and for P = 1 kW, and varying Q.

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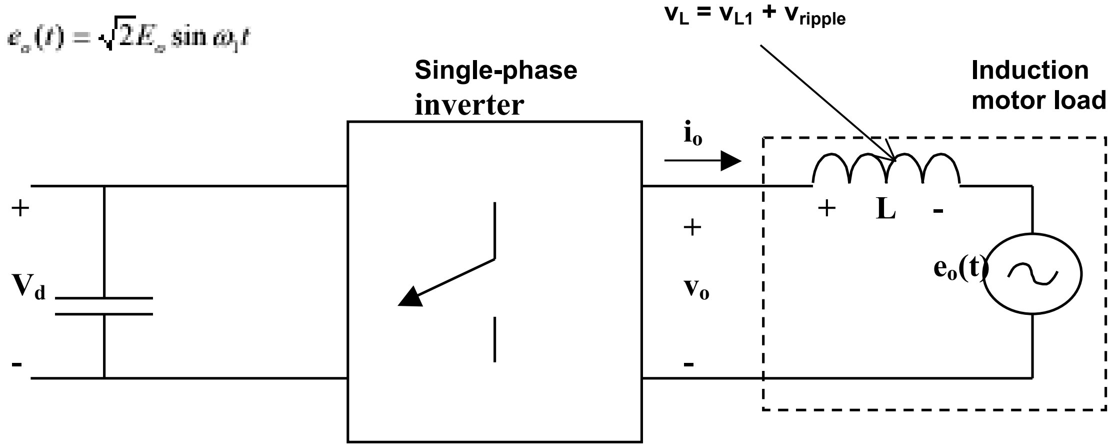
## S8.4 Single-phase full bridge converter




The problem with ripple in the output current from a single-phase full bridge converter is to be studied. The first harmonic of the output voltage is given by $V_{o1}$ at f = 47 Hz. The load is given in the figure as L = 100 mH in series with an ideal voltage source $e_o(t)$. It is assumed that the converter works in square wave mode.

(a) Calculate the value of $V_d$ which gives $V_{o1}$ = 220 V.

(b) Calculate the peak value of the ripple current.

The conditions are the same as in (a), but the converter operates in sinusoidal PWM-mode, bipolar modulation. $m_f$ =21 and $m_a$ = 0,8.

(c) Which value of $V_d$ gives $V_{o1}$ = 220 V?

(d) Explain why the ripple current has its peak value at the zero crossing of the first harmonic voltage, and find this value.

The conditions are the same as in (a), but the output voltage is given by voltage cancellation (see figure 8-17) and $V_d$ = 389 V.

(e) Calculate the "overlap angle" □ and peak value of the ripple current.

(f) Compare the values found in the three previous problems.

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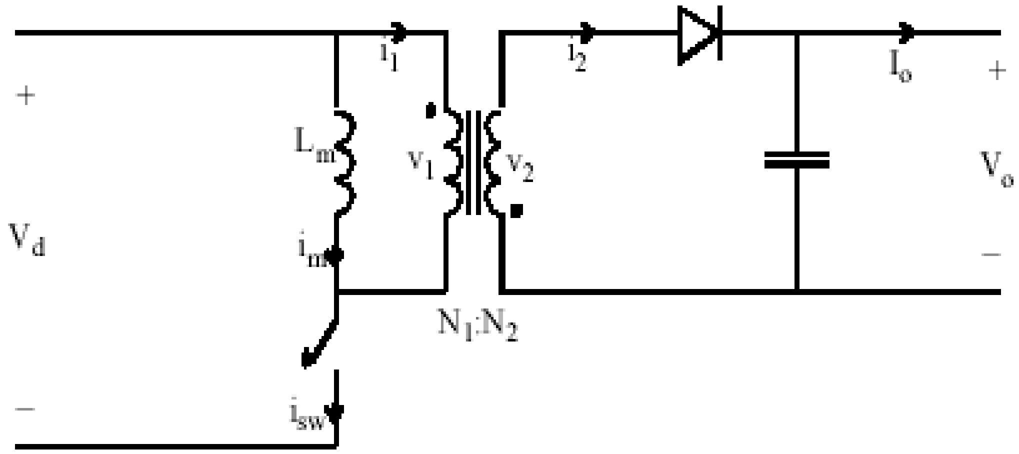
# Chapter 10

## S10.1 Flyback converter




$V_d$ = 300 V $V_o$ = 6 V D = 0.4
$I_o$ = 30 A $f_s$ = 100 kHz

The figure shows an equivalent circuit for the two-winding inductor. It consists of an ideal transformer and an ideal inductor (which equals the magnetizing inductance $L_m$).

(a) Calculate $N_1/N_2$.

(b) □$I_m = I_{m, max} - I_{m, min}$ is set equal to 0.2 A. Calculate $L_m$.

(c) Calculate maximum transistor current, $I_{sw, maks}$.

(d) Sketch $i_{sw}$.

(e) Find $v_{sw}$ during $T_{off}$

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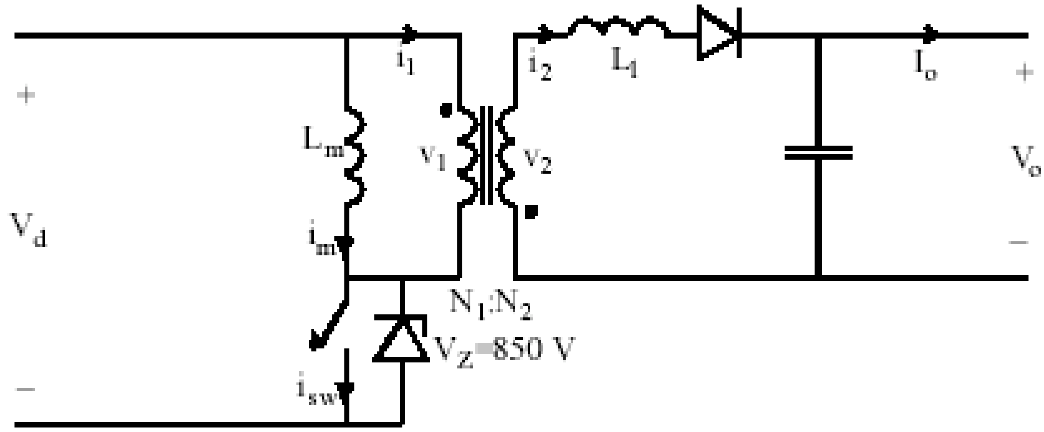
## S10.2 Flyback converter including effects of leakage inductance

Now, the leakage inductance of the transformer, $L_l$ is to be included in the calculations. The equivalent circuit will be as shown in the figure below. The current $i_2$ will, due to the leakage inductance, have a finite rise and fall time. Note the zener diode connected over the transistor. It has a zener voltage (*reverse breakdown voltage*) of 850 Volts.




$V_d$ = 300 V  $V_o$ = 6 V  D = 0.4
$I_o$ = 30 A  $f_s$ = 100 kHz

(a) Assume $L_l$ = 0,1 H. Find the rise time of $i_2$.

(b) Find the power losses in the zener diode.

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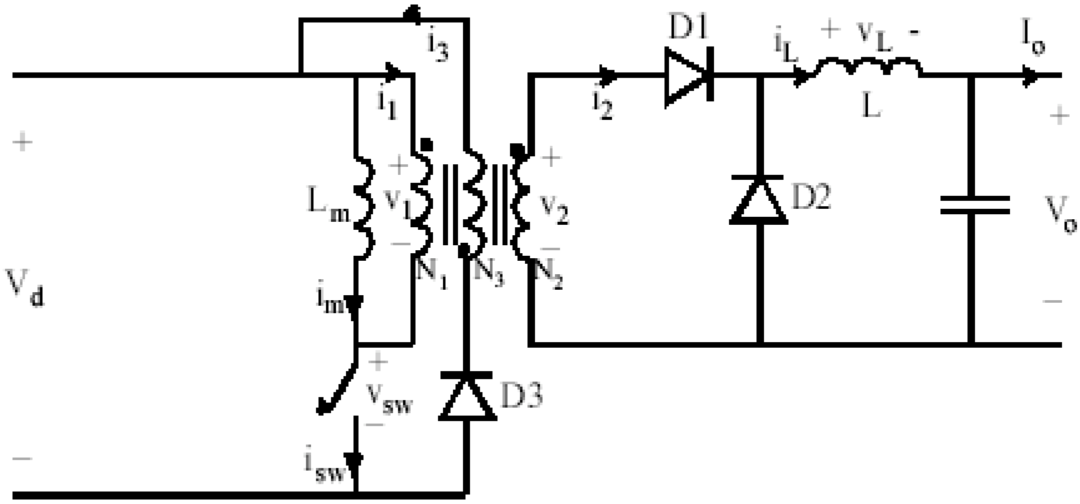
**S10.3 Forward converter**




$V_d$ = 300 V $V_o$ = 6 V $f_s$ = 100 kHz
$N_1:N_3$ = 1 $L_m$ = 15 mH L = 0.05 mH

(a) Calculate $D_{max}$.

(b) When D = 0.4, calculate the turns ratio $N_1:N_2$.

(c) When $N_1:N_2$ is as calculated in (b), what is the lowest input voltage allowed if $V_o$ is to be kept equal to 6 V?

In the following, D = 0.4.

(d) Calculate the voltage over the transistor during the $T_{off}$.

(e) Sketch $v_1$ and $v_{sw}$.

(f) For $I_o$ = 10 A, sketch $i_{D1}$ and $i_{D2}$.

(g) Sketch $i_{sw}$, $i_1$, $i_3$ and $i_m$.

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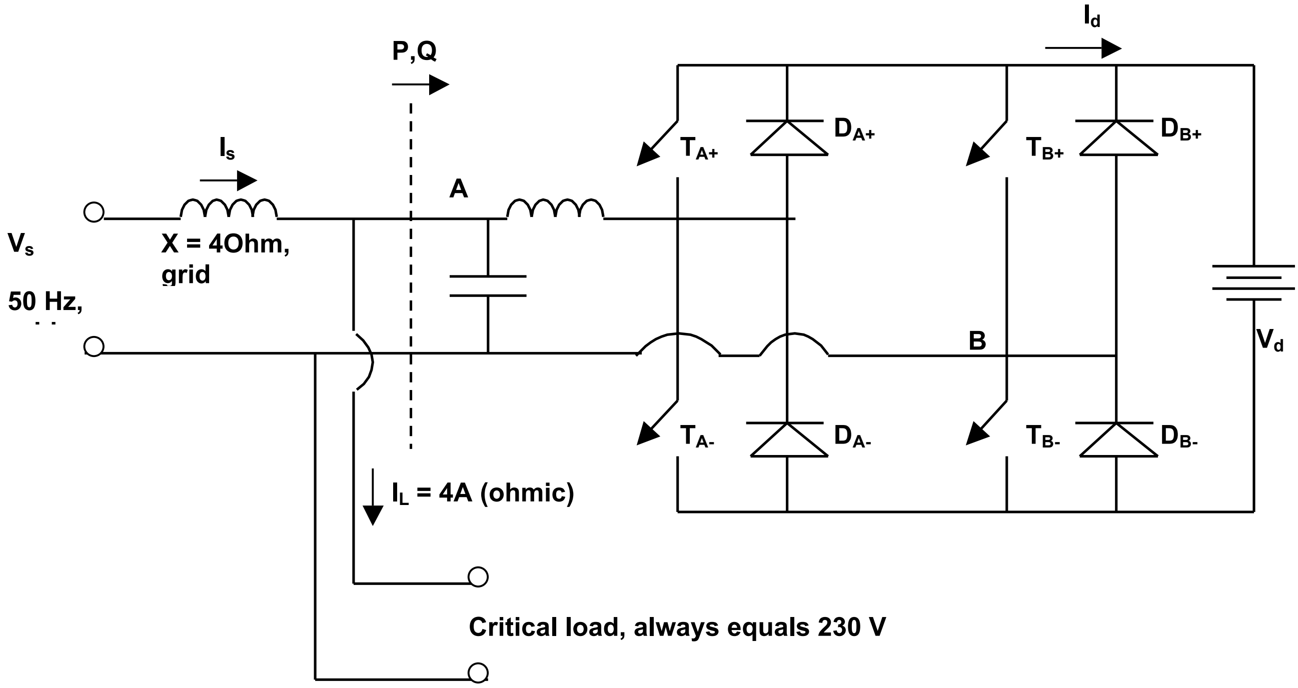
# Chapter 11

## S11.1 A UPS combining charging and inverter functions




The figure over shows a converter, which charges a battery. It also holds the critical load voltage stable at 230 V. (In case of grid failure, the converter will work as an inverter. See figure 11-12).

The battery voltage varies between 370 V (discharged) and 450 V (fully charged). The resistance of the battery is neglected.

At battery voltages below 450 V, the charging current is $I_d$ = 10A.

When the battery voltage has reached 450V, the converter switches to maintenance charging. Then the battery charging current is 0.5A.

Draw a phasor diagram, and calculate active and reactive power to/from the load, for the following situations:

| ***Problem*** | ***Battery voltage $V_d$*** | ***Charging current $I_d$*** | ***Grid voltage $V_s$*** |
|---|---|---|---|
| (a) Charging starts | 370 V | 10 A | 240 V |
| (b) Lower grid voltage | 450 V | 10 A | 220 V |
| (c) Maintenance charging @ 220 V | 450 V | 0.5 A | 220 V |
| (d) Maintenance charging @ 240 V | 450 V | 0.5 A | 240 V |

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## S11.2 UPS output filter, with low output reactance

The inverter of Fig. 11-10 is a full-bridge inverter with unipolar voltage switching PWM as described in Ch. 8-3-2-2. The output filter is a simple LC low pass filter. The switching frequency is 10 kHz. Due to the effects of blanking time on the output voltage as described in Ch. 8-5, there is 0.5 % 3.H and 0.3 % 5.H in the output voltage of the inverter in addition to the voltages described in Ch 8-3-2-2.

(a) For inverter output of 120 $V_{rms}$ 60 Hz sinusoidal fundamental and $m_a$ = 0.8, calculate $V_d$ .

(b) Assume 120 $V_{rms}$ at the filter output. The rated power of the UPS is 1kW, resistive load. Calculate the rated current.

(c) The parallel filter capacitor current is 5% of the rated current. Calculate $C_f$.

(d) The filter cut off frequency is 3 kHz. Calculate $L_f$.

(e) Calculate the most significant harmonics in the filtered output voltage, both at 3. and 5.H, and at close to 20 kHz. Will it make any difference if it is no-load or rated (resistive) load?

(f) Find the most significant filter currents close to 20 kHz.

(g) Calculate the 60 Hz reactance of the filter components.

(h) Find the no-load and the full-load 1.H output voltage.

## S11.3 UPS output filter, with medium output reactance

The inverter of Fig. 11-10 is a full-bridge inverter with unipolar voltage switching PWM as described in Ch. 8-3-2-2. The output filter is a simple LC low pass filter. The switching frequency is 10 kHz. Due to the effects of blanking time on the output voltage as described in Ch. 8-5, there is 0.5 % 3.H and 0.3 % 5.H in the output voltage of the inverter in addition to the voltages described in Ch 8-3-2-2.

(a) For inverter output of 120 $V_{rms}$ 60 Hz sinusoidal fundamental and $m_a$ = 0.8, calculate $V_d$ .

(b) Assume 120 $V_{rms}$ at the filter output. The rated power of the UPS is 1 kW, resistive load. Calculate the rated current.

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(c) The fundamental voltage drop over $L_f$ is 4 % of the rated output voltage. Calculate $L_f$

(d) The filter cut off frequency is 3k Hz. Calculate $C_f$.

(e) Calculate the most significant harmonics in the filtered output voltage, both at 3. and 5.H, and at close to 20 kHz. Will it make any difference if it is no-load or rated (resistive) load?

(f) Find the most significant filter currents close to 20 kHz.

(g) Calculate the 60 Hz reactance of the filter components.

(h) Find the no-load and the full-load 1.H output voltage.

## S11.4 Comparison of the UPS output filters

Compare problems S11.2 and S11.3.

(a) Comment on the difference in 20 kHz components of the filter currents even if the filters have the same voltage damping.

(b) Will the filter currents give significant contributions to the inverter transistor currents at rated load?

(c) Elaborate on the transient performance of an UPS with filter B, compared to one with filter C. For instance switch to full load from no-land.

(d) Do PSpice simulations on the UPS when the load is a 100% rated power diode rectifier into a capacitor that is modelled as a voltage source like the one in Fig. 5-16.

(e) Comment on the output ($C_f$) voltage and the current waveforms including their peak values.

(f) To compensate for the ripple in the output voltage, an output voltage regulator as shown in Fig. 11-10 may be used. Will filter B make other demands on the regulator than filter C?

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# Chapter 12

## S12.1 Conveyor belt with a slope.

A motor controls the speed of a conveyor belt with a mass M as shown in Fig. P12-2, except that the belt has a slope of $20^o$ and there is a gear between the motor and the drum.

| | |
|---|---|
| Mass of the load | $M = 3000$ kg |
| Inertia of the motor | $J_m = 0.3$ kgm$^2$ |
| Inertia of each drum | $J_{drum} = 45$ kgm$^2$ |
| Diameter of the drum | $D = 0.5$ m |
| Gear coupling ratio | $\frac{\omega_{drum}}{\omega_m} = a = 6.25$ |

Other inertias and friction are negligible.

(a) The belt moves the load uphill with a speed of v = 2 m/s. Calculate the motor speed, $\omega_m$.

(b) Calculate the total inertia $J_{tot}$ referred to the motor.

(c) Calculate the motor torque $T_{m,0}$ at standstill.

(d) Calculate the motor torque $T_{m,2}$ at 2 m/s uphill speed.

(e) The load accelerates in 1s from 0 m/s to 2 m/s, runs at constant speed for $1_s$, retards in 1s and is kept at standstill for 1s; like shown in Fig. P12-1.

1. Calculate $T_{em}$ required in these 4 intervals.

2. Calculate the $P_{em}$ for these 4 intervals.

3. Sketch the torque profile.

4. Sketch the power profile.

## S12.2 Paper roll in a printer.

In a newspaper-printing house the paper rolls are 1.2 m in diameter on a bobbin of 0.2 m in diameter. The paper fed to the printer must have a pull of 80N. The speed of the paper at printing is 50 m/s.

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An electric machine used to provide the constant pull is connected directly to the paper drum. Assume no losses.

a) Calculate the motor power at a full drum and when the drum is close to empty.

b) Calculate the machine speed and torque for a new paper roll.

c) Calculate the machine speed and torque for a close to empty paper roll.

d) Draw the power and the torque as function of speed.

## S12.3 Electric vehicle.

A small electric vehicle has a total mass of 1200 kg. At 50 km/hour on a horizontal road, the traction power needed is 5 kW.
Assume no losses.

(a) The traction battery is 210V. Calculate the battery current.

(b) The motor speed is $n_m$= 6000 rpm. Calculate the motor speed $\omega_m$ and the motor torque $T_m$. This is 1/10 of the maximum torque.

(c) The car runs uphill at a slope of 2 degrees and 50 km/hour. Calculate the motor torque $T_m$.

(d) Calculate the maximum slope at 50 km/hour.

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# Chapter 13

## S13.1 A speed controlled dc motor

A wound field dc motor has $R_a$ = 0.5 Ω. Rated values are: $V_{tr}$ = 220 V; $I_{ar}$ = 30 A; $P_r$ = 6.15 kW; $n_r$ = 1120 rpm; $\Phi_{fr}$ = 1 Wb @ $I_{fr}$ = 1 A

Rated voltages and currents cannot be exceeded.

(a) Why is $\Phi_f$ kept at its rated value in the whole lower speed range?

(b) Calculate the torque and the voltage constants of the motor.

(c) Characteristics at various speeds: Assume $I_a$ is kept at $I_{ar}$ for speeds between 0 and 1500 rpm. Calculate maximum possible $\Phi_f$ and $I_f$ as function of speed. Why is $\Phi_f$ kept to be as large as possible for a given speed?

(d) For the operation in (b), sketch as function of n: $T_{em}$; $P_{em}$; $V_t$; $e_a$ and $\Phi_f$.

(e) For $T_{load}$ = 0.7 $T_{loadr}$, calculate the maximum speed of the motor.

## S13.2 Field weakening

The dc motor in Problem 13 A must operate in field weakening above rated speed.

(a) List typical loads that allow for this kind of operation.

(b) What kind of loads will normally not allow field weakening?

(c) For loads that do not allow for the flexibility of field weakening, another type of dc motor may be used, which type is this?

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## S13.3 Dynamics in torque

Assume $L_a$ = 1 mH for the motor in Problem 13 A. The motor is connected to a buck converter with $V_d$ = 300 V.

(a) Assume the motor is running at 40 % of rated speed, at rated field and at 50 % of rated torque. Calculate the time needed to change the electromechanical motor torque to rated torque.

(b) Repeat the problem above, but now the motor is running at rated speed.

## S13.4 Dynamics in speed

Assume $L_a$ = 1 mH and its inertia 4 kgm for the motor in Problem 13 A. Assume that the load inertia can be neglected. The motor is connected to a buck converter with $V_d$ = 300 V. The motor controller has an inner current loop that limits the armature current to rated current.

(a) The motor is to be accelerated from 40 % of rated speed. Its field current is at rated value and the load torque is 50 % of rated value. Calculate the time needed for the change in the armature current assuming the motor speed is constant equal to 40 % of rated speed.

(b) Calculate the energy needed to vary the motor current to rated value.

(c) Assume a step in the armature current, calculate the time needed to accelerate the motor to 60 % of rated speed. Was it a fair to assume the step change in the motor current?

(d) At 60 % of rated speed the speed is to be kept constant. Calculate the change needed in the armature current. Calculate the time needed for this change in the current.

(e) Calculate the energy needed to change the speed due to the motor inertia.

(f) Sketch $V_t$, $I_a$, speed, $e_a$, power from the converter and power to the load for this acceleration.

(g) A cheaper motor controller without a measurement of the output current and an inner current loop is used. Assume maximum load to be 70 % of the rated value and the maximum inertia of motor and load combined to be 7 kgm. Calculate the maximum allowable ramp in the motor voltage during acceleration.

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# Chapter 14

## S14.1 Induction motor equivalent circuit

A three phase, two-pole induction motor is to be analyzed. A line-to-line voltage $V_s$ with a frequency f supplies the motor. The rotor speed is $\square_r$.

(a) Make a physical drawing of a cut of the stator. Depict $\square_{ag}$ in the drawing. Find the speed of the air gap field.

(b) What is the equation for the stator voltage component due to $\square_{ag}$? Use the definition of inductance and find this voltage as a function of magnetizing inductance and magnetizing current. Compare this to the primary winding of a transformer. Make a drawing of the equivalent circuit for the complete stator circuit, that is include stator resistance, leakage inductance and the magnetizing inductance. Depict where the air gap stator voltage is found in the equivalent circuit.

(c) The rotor speed is $\square_r$.. Find amplitude and frequency of the field in rotor due to the air gap field. Which name and symbol is used for this frequency?

(d) Calculate the induced voltage in the rotor and draw the rotor equivalent circuit including the rotor leakage inductance and resistance. Compare this to the secondary circuit of a transformer.

(e) The air gap flux, which is generated by the magnetizing current, is common for both windings in a transformer and both the stator and rotor windings of the induction motor. But in an induction motor the two winding have different frequency. Give a physical explanation for this.

(f) Multiply all components in the equation for the rotor circuit by $f/f_{sl}$. Prove that the rotor current is the same before and after this multiplication. Also prove that the voltages and power increase by the multiplication factor. Discuss where the total power was distributed before the multiplication and after. The power in the stator winding does not depend of this multiplication; the power in the rotor must be the same before and after.

(g) A better way to see the components of the active power in the rotor is to split the rotor resistor in two components. One is representing the losses in the rotor. What represent the power developed in the other rotor resistor component?

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(h) Describe the source for the magnetizing current. Compare with a transformer, and with the effects of increasing the torque on the motor, which induces increased currents, and the increase of the resistive load current in a transformer.

## S14.2 Induction motor, currents and power

An induction motor has these rated values:

Pr = 15 kW, $V_{ll,r}$ = 380 V, $f_r$ = 50 Hz, $I_r$ = 30 A, $\cos\varphi_r$ = 0.85
$n_r$ = 1464 rpm

The motor data are (all pr. phase):

$R_s$ = 0.3 Ω, $X_{ls}$ = 0.5 Ω, $X_m$ = 15 Ω
$R_r$ = 0.3 Ω, $X_{lr}$ = 0.2 Ω,

I. The motor is operating under stationary rated conditions, with fixed and rated voltage and frequency. This problem demonstrates an alternative way to calculate torque and currents at a specified slip.

(a) Draw the pr. phase equivalent circuit and indicate the variable representing the air gap flux.

(b) Select the $E_{ag}$ phasor real and equal to 220 V and draw the complete unscaled phasor diagram for the motor at rated conditions (that is for the machine data given above and the rated slip, but at too high voltages). The phasor diagram must include the stator pr. phase voltage Vs, stator current Is, rotor current $I_r$, magnetizing current $I_m$ and the induced air gap voltage $E_{ag}$. Also draw the air gap flux $\Phi_{ag}$.

(c) Since all components in the equivalent circuit are constant and linear, it is possible to correctly scale the above phasor diagram. That is the Vs value above must be adjusted to 220 V. This is a more straightforward way to find the phasor diagram for the motor than starting with calculating the parallel impedance of the rotor circuit and the magnetizing reactance, which then is put in series with the stator components to find the stator current. Anyway, the results will not be exactly as the rated values for the motor, in the above friction and iron losses are not included.

(d) Find the angle □ between Im and Ir. Calculate sin □.

(e) Find the power supplied from the line, stator and rotor losses and the mechanical output power.

II. Start from zero speed:

(f) Which simplifications can be done in the equivalent circuit at zero speed? Give an equation for the stator start current by using the simplified equivalent circuit. Calculate the current in A and in pu at start.

(g) The motor is designed to provide a torque at start that is say 1.5 of the rated torque. Explain that it is an advantage with a large Rr at start, while it is an advantage with a small Rr at steady state operation with slip below rated slip.

(h) The use of deep bar rotor makes the Rr to increase as the rotor frequency increases. Thus the effect described above can be obtained. If it is possible to obtain the specified torque at start with lower currents than calculated in (f), in what ways can the currents be reduced?

(i) By the use of a variable voltage/frequency control the start currents can be reduced and the torque at start can be controlled easily above 2 times the rated torque. Explain how the motor voltage and frequency must be adjusted to provide this.

III. Torque – speed characteristic:

(j) When $f_{sl}$ is small compared to f: Simplify the equivalent circuit for the induction motor. Find the rotor current Ir and the electromechanical torque Tem as a function of the slip frequency when assuming Eag is kept constant and equal to the value used in (b).

(k) When fsl is large (from 0.5 to 1) the currents are basically as found in (f)

(l) Sketch the motor torque and the rotor current as function of the slip frequency in the range 1 to 0. Use pu values in the sketch.

## S14.3 Frequency control, saturation at low speed

An induction motor has these rated values:

Pr = 15 kW, $V_{ll,r}$ = 380 V, $f_r$ = 50 Hz, $I_r$ = 30 A, $\cos\varphi_r$ = 0.85
$n_r$ = 2928 rpm

The motor parameters are (all pr. phase):

$R_s$ = 0.3 Ω, $X_{ls}$ = 0.5 Ω $X_m$ = 15 Ω
$R_r$ = 0.3 Ω, $X_{lr}$ = 0.2 Ω

At rated air gap flux the magnetizing current is 10 A, and below this it is a linear function of the magnetizing current. Above it is also a linear function, but for 1.1 of rated flux, the magnetizing current is 25 A.

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(a) Why should the air gap flux be kept constant and equal to its rated value at any speed below rated speed?

(b) Which equation gives the relation between $E_{ag}$, $\Phi_{ag}$ and the frequency f of the voltage supplied to the motor? Make a sketch of $E_{ag}$ as function of f, for frequencies between 0 and 50 Hz.

(c) Derive the equation for the mechanical power $P_{em}$ and torque $T_{em}$ as function of rotor current $I_r$ and the slip frequency $f_{sl}$. For a given rotor current and slip frequency, will the torque vary if the stator voltage frequency f varies?

(d) It can be shown that at rated conditions, Eag = 204.9 V and Im = 13.7 A $\angle$-90. Draw the phasor diagram. At rated stator voltage and frequency but at no load (also neglect windage and friction losses), calculate the air gap voltage and the magnetizing current.

(e) The motor is to run at low speed. The stator frequency is reduced to 2 Hz. The load torque is equal to the rated torque. Calculate the stator voltage that gives rated value of the air gap flux $\Phi_{ag}$. Draw a phasor diagram for this operation.

(f) Assume zero speed and the motor voltage as found in (e) at 2 Hz. Calculate the start current and the start torque.

(g) The motor voltage is as in (e) and the motor load is zero, also friction losses as described in (d). Calculate $E_{ag}$ and $I_m$. Use the magnetizing characteristic and iterate until reasonable results are found. Simplify the calculations. Calculate the stator current and compare with (e).

## S14.4 Induction motor at over harmonic voltages

An induction motor is fed with a voltage Vs containing harmonic components. Some of these are:

1. harmonic = $V_{s1}$
5. harmonic = 0.2 $V_{s1}$
7. harmonic = 0.14 $V_{s1}$

(a) Write the mathematical expression for all the three phases for these three voltages as function of time. Use the angular frequency $\omega_1$, $\omega_5$ and $\omega_7$ in the equations. At the zero crossing of the sinusoidal voltages there is no phase shift between the different harmonic components in the voltages.

(b) Substitute $\omega_1 = \omega_s$, $\omega_5 = 5\omega_s$ and $\omega_7 = 7\omega_s$ in the equations. Draw a phasor diagram for each harmonic component.

(c) Find the air gap flux due to the 5. and 7. harmonic. Calculate the speed and the direction of the two harmonic components.

(d) Find the interaction between the 5.H and the fundamental. Also find it for the 7.H and the fundamental. Illustrate the total interaction.

(e) In which way will these results influence torque and speed at a given operating condition? Indicate how the ripple in the speed depends on the actual speed.

## S14.5 Control by only varying the voltage, not the frequency

The speed is to be varied for a fan motor. The motor is supplied with a 60 Hz voltage, which value can be controlled, in this way the speed of the motor and the fan can be controlled. The fan load torque is proportional with the speed squared.

(a) Make a sketch of how input and power vary with the speed, and indicate on the sketch the difference of these two, which are the losses.

(b) Prove that the maximum motor losses are approximately $\frac{4\, T_r \omega_s}{27}$. $T_r$ is the torque at rated speed.

(c) The power at rated speed is 1 kW. A motor with rated slip of 3 % is used. Calculate the rated power of this motor if it is not to be overloaded at any speed.

(d) As (c) but rated slip is 10 %.

## S14.6 Speed control of induction motors

Assume $V_s = E_{ag}$.

(a) Show the relation between $V_s$ (= $E_{ag}$), $\Phi_{ag}$ and $f$ (f is the frequency of the applied stator voltage).

(b) Why should $\Phi_{ag}$ be kept constant at its rated value when the motor speed is controlled below its rated value?

Operation above rated speed. Show the relation between $V_s$ and speed when $\Phi_{ag}$ is kept constant. Why is this normally not used?

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(c) Sketch $V_s$ as function of $f$ as it should be. Make the sketch for frequencies between 0 and $3f_{rated}$. Show the equation for $\Phi_{ag}$ for frequencies above the rated frequency ($f_{rated}$).

From machine theory: $T_{em} = k \ \Phi_{ag} \ I_{rotor} \ \sin\delta$

(d) Make use of the equation above to find the equation for $T_{em}$ as function of $\Phi_{ag}$ and $f_{sl}$.
Combine $\Phi_{ag}$ from (d) with the equation for $T_{em}$ found above.

(e) In (d) it is assumed: $2\pi f_{sl} L_{lr} << R_r$. When is this assumption valid? Discuss the answer.

(f) Make a sketch of the torque-speed characteristics where the assumption is valid. Sketch four characteristics for the stator frequencies: $f_{rated}$, $1.2f_{rated}$, $1.5f_{rated}$, and $2.0f_{rated}$. Comment the characteristics.

(g) Assume the slip $f_{sl}$ is kept constant when the frequency increases above the rated frequency ($f_{rated}$). Show the characteristics for
- power $P$
- stator and rotor currents in the machine.
- losses in the machine.

(h) Is the machine fully utilized when controlled as described above?

(i) The machine is to be controlled in a way that the rotor losses are kept constant for frequencies above rated frequency. Show the characteristics for:
- torque $T_{em}$
- power $P$
- slip frequency $f_{sl}$

(j) Can the control described in (i) be used in the high frequency range? Show the torque characteristic in the high frequency range. It is possible to achieve a larger torque above rated frequency or speed. Explain how cooling and winding isolation will allow this.

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# Chapter 15

## S15.1 Permanent magnet synchronous motor

A two-pole permanent magnet synchronous motor with sinusoidal flux distribution in the air gap and sinusoidal distributed stator winding has these data:

Voltage constant: $k_E$ = 0.012 V/rpm, Line-line rms voltage
Stator resistance: Rs = 0.83 Ω/phase
Leakage inductance: $L_{ls}$ = 1.0 mH/phase
Synchronous inductance: Ls = 9.5 mH/phase

(a) For permanent-magnet (PM) sinusoidal motor drives, the torque angle $\delta$ is kept constant equal to 90° and the field-flux $\Phi_f$ is constant. The torque can then be calculated as shown Eq. 15-22 in the textbook. $I_s$ is the max-value of the stator current. Calculate the torque constant $k_T$ of the motor.

(b) Draw a pr phase equivalent circuit of the motor. Which of the voltage variables in the circuit represent the air gap flux and the rotor field?

(c) The motor speed is n = 3,000 rpm. The load is Pem = 300 W. Calculate currents and voltages of stator. Let $E_{fa}$ be along the real axis, and draw the phasor diagram with both currents and voltages. Also, draw the d- and q-axis and the flux phasors. Indicate the torque angle $\delta$ and the line phase angle $\phi$.

## S15.2 Load-commutated inverter fed synchronous motor

The converter and motor configuration is as shown in Fig. 15-7. The 3-phase windings are like shown in Fig. 15-1 or as indicated in Fig. 14-27a.

(a) List the most important characteristics of this class of motor drives. Include advantages and disadvantages in the list.

(b) Discuss the order of the firing pulses to get the motor to rotate counterclockwise. Label the thyristors as a+, b+ and c+ for those connected to the positive voltage, and a-, b- and c- for the others. Start with a+ and b- conducting.

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The synchronous motor has a speed of half of the rated speed. The magnetizing current is kept at the value that gave rated terminal voltage at rated speed and no load. The load at this operating point gives rated stator current. Assume ideal commutation and the extinction angle is kept to be 30°. At rated speed the synchronous reactance is 0.9 pu. Neglect the stator resistance.

(c) Sketch the voltage and current waveforms in all three phases.

(d) Sketch the phasor diagram

(e) Calculate the torque angle $\delta$ and the power factor $\cos\varphi$ for this operating point.

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# Chapter 16

## S16.1 Integral half-cycle control of electric heating elements

Resistive heating is used a lot in industry where consentrated heating that can be controlled is needed.

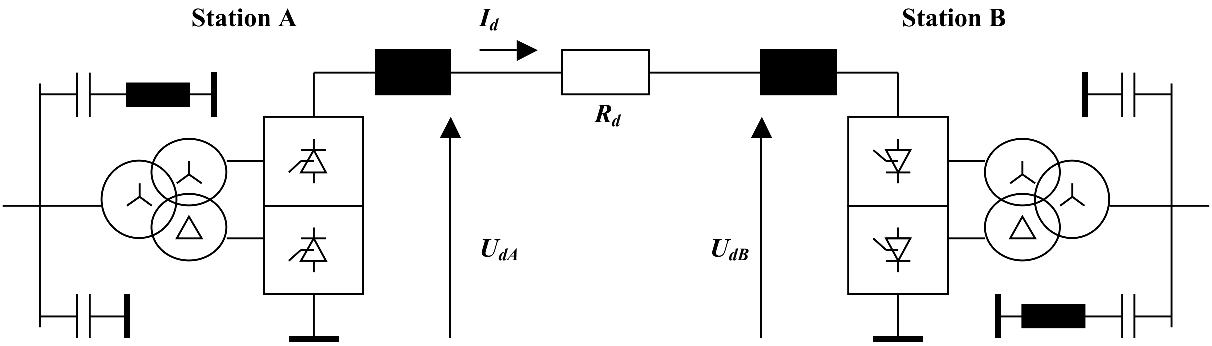
(a) Why is integral half-cycle used as shown in Fig.16-10 , and not the delay-control shown in Fig. 2-4?

(b) In Fig. 16-10, m = 1000. For a single-phase load directly connected to the load the power is 800 W. Find the number of half-cycles n the thyristors must be controlled to be on for 250 W in the load.

(c) The high number of pulses is used both for smooth regulation and to avoid flicker in the light connected to the same outlet as the electrical heater. Explain why.

# Chapter 17

## S17.1 HVDC transmission




**Monopolar HVDC transmission**

The rated voltage on the thyristor-side of the rectifier transformers is 156 kV. The rated current for the dc transmission is $I_d$ = 1.25 kA.

(a) The figure shows a monopolar HVDC transmission. The converters in station A and B are both connected to identical transformers with tap-changers. The pu reactive voltage drop over at transformers at rated current is $e_{sc}$ = 0.04. Calculate the transformer reactance.

(b) Station A is supplied by rated ac voltage. The station B operates at $\gamma_{min} = 18^{o}$ and ac voltage is 4% below the ac voltage of the A station. $I_d$ = 1.00 kA. Calculate $U_{dB}$, $U_{dA}$ and firing angle $\alpha$ in station A.

(c) Calculate the commutation angle $u$ in station A and station B. Why is tap-changer transformers used in station A and B.

(d) Find the phase angle between line voltage and fundamental line current that that is fairly accurate when commutation angle is considered.

(e) Calculate the active and the fundamental reactive current supplied by the line to the station A.

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## S17.2 HVDC, reactive power

(a) Explain why an HVDC-converter needs reactive power from the grid. Use sketches to illustrate the explanation. Include both rectifier mode and inverter mode of operation.

(b) In what way should the firing angle and the extinction angle be controlled to minimize reactive power consumption?

(c) List factors for the limitations on the firing angle and the extinction angle.

(d) Explain how the step adjustment on the converter transformer may be controlled to achieve optimum firing angle in rectifier mode.

(e) Describe the goal when controlling the step adjustment on the transformer on the inverter side

(f) Capacitor batteries and passive filters are frequently used to compensate the reactive power consumption of the HVDC-converter. Explain why this may be unfavorable in case of grid voltage reduction, and in case of rapid reduction in the active power of the HVDC-converter.

(g) Explain how the use of FACTS components may improve the situation described in (f).

## S17.3 HVDC, commutation failure

When controlling an HVDC-converter in inverter mode, commutation failure may occur. During a commutation failure the thyristor that should be switched off continues conducting, and the dc voltage on the inverter side of the dc transmission will reverse. Thus the dc current will increase very fast, making commutation failure even more likely. An inverter station may override 2 commutation failures. If the problem is not solved, the dc transmission had to shut down.

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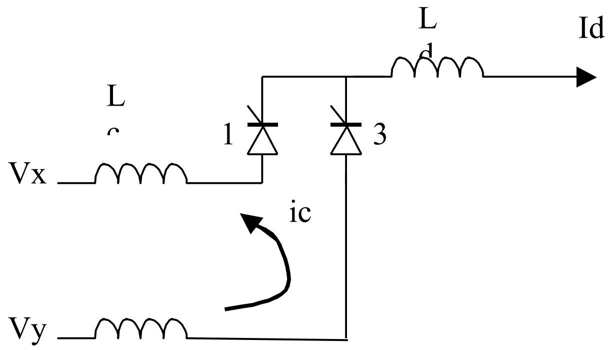


Assume that the dc smoothing inductor is so large that $I_d$ may be considered constant. Assume thyristor 1 conducts. As thyristor 3 gets a firing pulse, the current starts commutating from thyristor 1 into thyristor 3.

(a) Sketch in the same figure a typical waveform of the current through thyristor 1 and thyristor 3 during the commutation interval.

(b) Find the equation for the commutation current $i_c$.

(c) Find $i_c$ at the end of the commutation.

Assume $V_y$-$V_x$= $\sqrt{2}\, V_{LL} \cos\omega t$.
The commutation angle is equal to u.

Suddenly, something happens in the main grid, and $V_x$ - $V_y$ drops. The current $I_d$ is assumed to be constant.

(d) Will this increase or reduce the commutation angle?

(e) Explain how commutation failure may occur during inverter operation.

## S17.4 Photovoltaic

A photovoltaic array is to be used in telecommunication to charge a 12 cells (or 24 V nominal) lead-acid battery. A battery may be damaged if it is discharged below 1.6 V/cell. Maximum voltage is 2.27 V/cell.

(a) Calculate the voltage range of the battery.

(b) Find the % change in the battery voltage with respect to its nominal voltage.

(c) Redraw Fig. 17-12 for power as function of voltage for

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$P_l$ = 100 mV/cm$^2$ at 64 °C, for 75 mV/cm$^2$ at 64 °C, for 50 mV/cm$^2$ at 28 and 64 °C.

(d) Assume the array is directly connected directly to the battery. At insolation of 50 mV/cm$^2$, find the number of cells needed to provide a charging current of 1.1 A at any temperature between 0 and 64 °C.

(e) Assume in a typical hour, each of the 4 operation conditions in (c) lasts for 15 min. Calculate the energy available to charge the battery in one hour when its voltage is close to the maximum voltage.

(f) As (e), but the battery is close to being discharged.

(g) Which converter is best suited for interfacing the photovoltaic array and the battery?

(h) A step-down converter with no losses and control to provide the maximum power point tracking is interfacing the photovoltaic array and the battery. Assume insolations as in (e) and calculate the charging energy in one hour when the battery voltage is close to its maximum value.

(i) As (h), but the battery is close to being discharged.

(j) 5 photovoltaic arrays are paralleled and connected directly to a 24 V battery bank. If a step-down chopper were used in the interface between the arrays and the batteries, could the number of parallel arrays be reduced for the same charging pr hour?

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