Bundle of exams Electronic Power Conversion (ET4119)

February 2000 – January 2007

Remarks:

In front of every question the maximum rating that can be obtained is indicated.

First solve the problems for your self on draft paper and make a neat version subsequently.

Start each problem on a separate piece of paper.

Always show the formulas that you used to make the calculations.

You can give your answers in Dutch or in English.

It is allowed to use a (self-made) piece of paper (1xA4) with formulas and figures from the textbook.

Note:
- The answers in this bundle are in short from. A more elaborate answer, showing methods and applied formulas, is expected from you at the exam.
- Please inform me about (typing) errors in this bundle: s.w.h.dehaan@tudelft.nl

Exam *Electronic Power Conversion* 4 February 2000 (selection)

(80) PROBLEM 1
Given is a simple circuit with a generic switch as shown in the figure 1a.

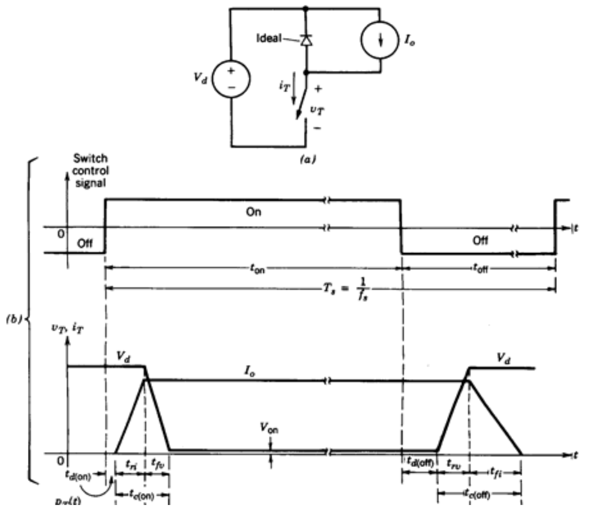


Fig. 1

The data sheet of the switch specifies the following switching times corresponding to the linear switching characteristics as shown in the figure.

t_{ri} = 80 ns ;
t_{fv} = 80 ns ;
t_{rv} = 120 ns ;
t_{fi} = 200 ns

Further: V_d=300V ;
I_0 = 4A.

(10) 1.1 Sketch the instantaneous switching loss as a function of time
(40) 1.2 Calculate the switching power loss as a function of the switching frequency in a range 25 - 100 kHz, assuming V_d=300V and I_0 = 4A.
(30) 1.3 Calculate and plot the total losses as a function of the switching frequency in a range 25 - 100 kHz in the switch when the on-state voltage is V_{on} =1.5V at 4A and the duty ratio of the switch is D = 0.4 (assume $t_{don}=t_{doff}$).

Summary of answers to exam *Electronic Power Conversion* dd 4 February 2000

1.2 $E_{loss,sw}$ = 1/2 I_o V_d ($t_{ri}+t_{fv}$) + 1/2 I_o V_d($t_{rv}+t_{fi}$) =
= 1/2 4.300($t_{ri}+t_{fv}$ + $t_{rv}+t_{fi}$) = 288 μJ
$P_{loss,sw}$ = f_s . $E_{loss,sw}$ = 288 f_s μW

1.3 $P_{loss,on}$ = V_{on} . I_{on} t_{on}/T_s = V_{on} . I_{on} D = 2,4 W
$P_{loss,tot}$ = 2,4 + 288. 10^{-6} f_s W

Exam *Electronic Power Conversion* 7 April 2000

(190) PROBLEM 1

Given converter shown Fig. 2, consists of a forward converter that is connected to the grid (230V, 50Hz) via a diode rectifier.

The following is given:

f_s = 80 kHz (switching frequency of the forward converter)

L_0 = 25 μH

R_o = 4 Ω

W_1:W_2:W_3 = 230:115:10

Both C_1 en C_o are sufficiently large to justify the assumption of u_1 and u_o being constant. The forward converter is lossless and can operate in both continuous and discontinuous conduction mode.

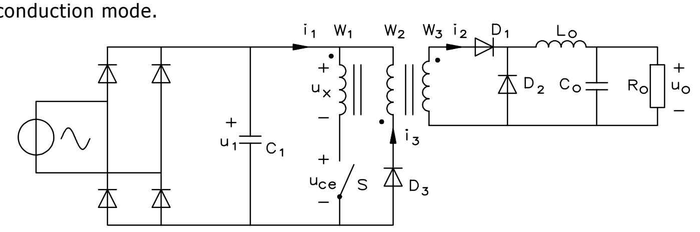


Fig. 2

(10) 1.1 Calculate the voltage u_1 across C_1.

(20) 1.2 Describe the function of winding w_2 and diode D_3.

(30) 1.3 Calculate the allowable control range of the duty ratio D.

(30) 1.4 What values can the output voltage take when the duty ratio is varied over the allowable control range. Consider both continuous and discontinuous conduction mode.

(30) 1.5 Calculate D for an output voltage of 5V.

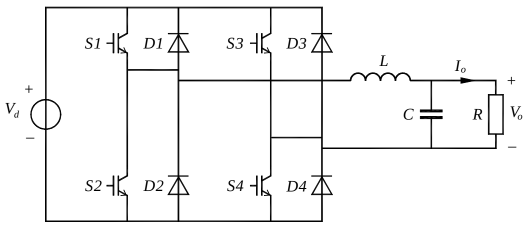
(30) 1.6 Sketch the course of i_1, i_2, i_3, i_L, u_{ce} and u_1 as a function of time. Mark the graph with values.

(30) 1.7 Calculate the critical inductance L_c as a function of the duty ratio D.

(30) 1.8 Sketch the current i_s through the ac supply and calculate the input power.

(120) PROBLEM 2

Given is a full-bridge dc-dc converter (H-bridge) with RLC-load as shown. For control of the switches so called bipolar voltage switching is applied, were the control signals are obtained by comparing a control signal $v_{control}$ with a triangular waveform $v_{tri.}$



The following is given:

T_s= 1 ms (T_s is the period of triangular waveform)

R=5 Ohm

L=2 mH

V_d=300V

V_0=120 V (Desired output voltage)

C is sufficiently large to assume the output voltage to be constant.

(15) 2.1 Express the output voltage in V_d and $v_{control} / \hat{v}_{tri}$.

(15) 2.2 Define the duty ratio D and calculate the required duty ratio to get an output voltage of 120V.

(30) 2.3 Sketch the $v_1(t)$, $i_L(t)$ and the source current i_d.

(30) 2.4 Indicate in the sketch what switches are conducting at what time.

(30) 2.5 Express the ripple in the output voltage ΔV_0 in L, C, D and T_s.

(50) PROBLEM 3

(20) 3.1 Define the switch utilisation ratio.

(30) 3.2 Calculate the switch utilisation ratio for a step-up and a step-down converter as a function of the duty ratio D were inductors and capacitors are sufficiently large to assume that inductor currents are constant and capacitor voltages are constant.

Summary of answers to exam *Electronic Power Conversion* dd 7 April 2000

1.1 $U_1 = 230\sqrt{2} = 325$ V (peak rectification)

1.2 Function of w2: to reset the core and to avoid that the magnetisation energy is dissipated into the switch at turn off. Function of D2: avoid that an increasing dc-current will start to flow through w2.

1.3 >$\Delta B_{up} = \Delta B_{down}$= ; $\frac{1}{w_1 A} U_1 \; D T_s = \frac{1}{w_2 A} U_1 \; (1-D) T_s$

so: 0 < D < 2/3

1.4 Continuous: $U_0 = D \frac{10}{230} \cdot 325$ with 0<D<0.667

Discontinuous: $D \frac{10}{230} \,.\, 325 < U_0 < \frac{10}{230} \,.\, 325$ with 0<D<0.667

So: 0< U_o < 14,2

1.5 Continuous conduction mode: $U_0 = D \frac{w_3}{w_1} U_1$

$$D = \frac{w_1}{w_3} \frac{U_0}{U_1} = \frac{230}{10} \cdot \frac{5}{325} = 0.35$$

1.6 See book

1.7 $L_c = (1-D) \frac{R}{2 f_s}$

1.8 P_{in}=P_{out} ; $P_{out} = \frac{U_o^2}{R_0} = \frac{25}{4} = 6.25\,W$

2.1 $V_o = \frac{v_{control}}{\hat{v}_{tri}} V_d$

2.2 $V_0 = (2 D_1 - 1) V_d \quad (= \frac{v_{control}}{\hat{v}_{tri}} V_d)$

$\frac{v_{control}}{\hat{v}_{tri}} = 0.4$; D_1 = 0.7

2.3 Like Mohan fig 7-28

2.4 (D1+D4), (S1+S4), (D2+D3), (S2+S3), (D1+D4), ..., 2.5 $\Delta V_0 = \frac{D(1-D)}{8LC f_s^2} V_d$

3.1 See Mohan par. 7.8 and 8.3.4
3.2 See Mohan par. 7.8 and 8.3.4

Exam *Electronic Power Conversion* 27 January 2001 (selection)

(120) PROBLEM 1
The converter shown in Fig. 3 consists of a forward converter that is connected to the grid (230V, 50Hz) via a diode rectifier.
The following is given

f_s = 80 kHz (switching frequency of the forward converter)
L_0 = 25 µH
R_o = 4 Ω
W_1:W_2:W_3 = 230:115:10

Both C_1 en C_o are sufficiently large to justify the assumption of u_1 and u_o being constant.
The forward converter is lossless and can operate in both continuous and discontinuous conduction mode.

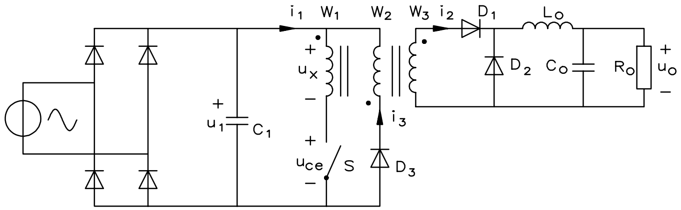


Fig. 3

(10) 1.1 Calculate the voltage u_1 across C_1.
(20) 1.2 Describe the function of winding w_2 and diode D_3.
(20) 1.3 Calculate the allowable control range of the duty ratio D.
(20) 1.4 Calculate D for an output voltage of 5V.
(30) 1.5 Sketch the course of i_1, i_2, i_3, i_L, u_{ce} and u_1 as a function of time. Mark the graph with values.
(20) 1.6 Sketch the current i_s through the ac supply and calculate the average input power.

Summary of answers to exam *Electronic Power Conversion* dd 26 January 2001

1.1 $U_1 = 230\sqrt{2} = 325\,V$ (peak rectification because the capacitor C_1 is large).
1.2 Function of w2: to reset the core and to avoid that the magetisation energy is dissipated into the switch at turn off. Function of D2: avoid that an increasing dc-current will start to flow through w2.
1.3 >ΔB_{up} = ΔB_{down}= ; $\frac{1}{w_1 A} U_1\, D T_s = \frac{1}{w_2 A} U_1\, (1-D) T_s$
so: 0 < D < 2/3
1.5 Continuous conduction mode: $U_0 = D \frac{w_3}{w_1} U_1$

$$D = \frac{w_1}{w_3} \frac{U_0}{U_1} = \frac{230}{10} \cdot \frac{5}{325} = 0.35$$

1.6 See Mohan fig. 10-11

Exam *Electronic Power Conversion* (ET 4-119) dd 21 March 2001 (selection)

(60) PROBLEM 1
For applications such as motors and servo control it is often required to control the motor current. There are various ways to obtain switching signals for the switches to control the inverter output current.
In Fig. 4a phase leg of a voltage source inverter is shown.

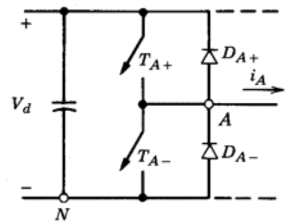
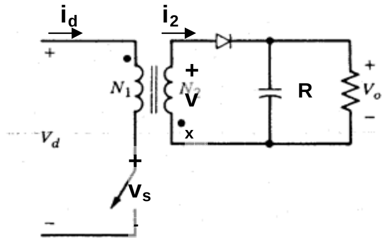


Fig. 4

(40) 1.1 Describe a system to control the output current i_A of the inverter leg in Fig. 4. Give a block diagram of the system and sketch the voltage v_{AN}, i_A and the on/off signals for the switches.
(20) 1.2 What parameters in the control system determine the magnitude of the current ripple and how can a small current ripple be obtained.

(70) PROBLEM 3
Given is a flyback converter as shown in Fig. 5b. The input voltage V_d may vary and the output voltage V_0 should be kept constant by adapting the duty ratio D.



(b)

Fig. 5

Given is:
V_d = 12 ...14 V
V_0= 48 V
N_2/N_1 = 6
f_s = 200 kHz
R_0=10 Ohm

(10) 3.1 Derive the voltage transfer function V_0/V_d in continuous conduction mode (incomplete demagnetisation mode) as a function of the duty ratio D and calculate the duty ratio for V_d=12V.

(20) 3.2 Calculate the minimum value of the transformer inductance L_m that is required to obtain continuous conduction mode for all values of V_d in the range 12 …14V.
Hint: Be aware that at the boundary of the continuous/discontinuous conduction mode the following holds: $D\,\hat{i}_d/2 = I_d$ and $I_d V_d = P$.

(20) 3.3 Calculate the maximum voltage across the switch.

(20) 3.4 Sketch i_d, i_2, v_x and v_s as a function of time for V_d = 12V.

Summary of answers to exam *Electronic Power Conversion* dd 21 March 2001

1.1 See book of Mohan par 8.6.3 fig 8-35 or 8-36

1.2 Fig 8-35: the tolerance band
Fig 8-36: the frequency of v_{tri}
(Other factors outside the control system: the supply voltage, the back EMF and load inductance).

3.1 $V_0 = V_d \dfrac{N_2}{N_1}\dfrac{D}{1-D}$; D= 0.4; (At V_d=14 V the duty ratio is D=0.36)

3.2 The boundary is reached at the highest input voltage V_d=14V with D=0.36
At the boundary of continuous conduction: $D\,\hat{i}_d/2 = I_d$ with $I_d = P_o/V_d$ = 230.4 /14 =16.5 A

Also: $\hat{i}_d = \dfrac{V_d}{L_m} DT_s$ or $L_m \ge \dfrac{V_d}{\hat{i}_1} D_s T_3$ with $\hat{i}_d = \dfrac{2I_d}{D} = \dfrac{2\cdot 16.5}{0.36} = 91.7$ A

So $L_m \ge \dfrac{V_d}{\hat{i}_1} D\,T_s = \dfrac{14}{91.7}\cdot 0.36\cdot 5\cdot 10^{-6} = 0.275 \quad \mu H$

3.3 $v_s = V_d + v_{x1} = V_d + \dfrac{N_1}{N_2} V_0 = 14 + \dfrac{48}{6} = 22 \quad V$

3.4 See Mohan fig 10-8

Exam *Electronic Power Conversion* dd 25 January 2002 (selection)

(30) PROBLEM 3

A forward converter with demagnetisation winding (with $N_3=N_1$) as shown in Fig. 6 is to be designed with the following specifications:

V_d = 48V ±10%
V_0 = 5V (regulated)
f_s = 100 kHz
P_{load} = 15-50W
$N_1 = N_3$

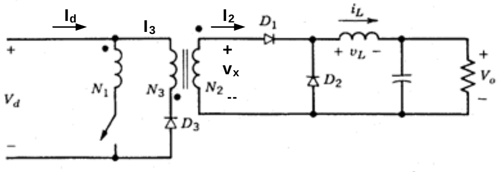


Fig. 6

Assume all components to be ideal except for the presence of the transformer magnetization inductance. The winding N_3 serves complete demagnetization of the magnetization inductance of the core.
The converter operates in continuous conduction mode for all given supply and load conditions

(5) 3.1 Calculate N2/N1 if the turns ratio is desired to be as small as possible(10)

3.2 Calculate the minimum value of the output filter inductance L to guarantee continuous conduction mode for all specified load and supply conditions.

(15) 3.3 Sketch the waveforms of v_x, i_L, i_2, i_3, i_d for V_d = 43,2V and P_{load} =15W and L=L_{min}

(25) PROBLEM 4

Given is a bi-directional single-phase dc/ac converter that is connected to a grid with voltage e_0, as shown in Fig. 7.

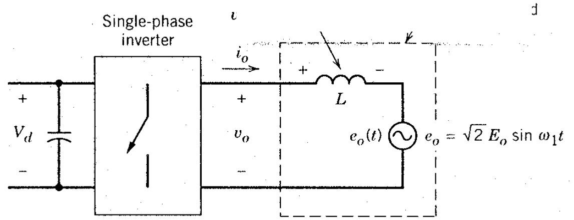


Fig. 7

The output voltage v_0 of the inverter, that contains a full-bridge voltage source converter, is obtained by bipolar voltage switching as shown inFig. 8. Only linear modulation is applied (no overmodulation).

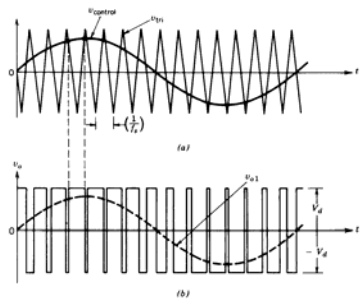


Fig. 8

Given is further: V_d = 350V

$e_0 = E_0\sqrt{2}\sin\omega_1 t$ with E_0 = 230V and $\omega_1 = 2\pi 50$

L = 15 mH

The inverter is fed from a photovoltaic array and the objective is to supply power to the grid at unity power factor. In the following questions the ripple that is caused by the switching can be neglected.

(5) 4.1 Define the modulation ratio m_a and give the relation between V_o, m_a and V_d, where V_o is the rms fundamental of the output voltage.

(10) 4.2 Sketch a phasor diagram with the phasors of e_0, v_0 and i_0 . Calculate the modulation ratio m_a such that 1 kW is supplied to the grid at unity power factor (pf=1) in e_0.

(10) 4.3 What is the lowest value of V_d where we can still supply 1 kW to the grid with linear sinusoidal modulation?

Summary of answers to exam *Electronic Power Conversion* dd 25 January 2002

3.1 See problem 10.5 in Mohan's book. $V_0 = V_d \frac{N_2}{N_1} D$. The highest D will be used at the lowest value of V_d or V_d=43.2V. To guarantee continuous conduction for all load and supply conditions: $N_2/N_1>0.23$.
(Note: when N_2/N_1=0.23 and V_d=52.8V, the duty ratio can be reduced to 0.408 to obtain 5V)

3.2 For a given L discontinuous mode will first occur at light load (P_{load}= 15W) and D=0.5, which is also the maximum allowable value of D.

At boundary (see eq. 7.5 in Mohan): $\frac{1}{2}\frac{(V_d \frac{N_2}{N_1} - V_0)}{L_{min}} t_{on} = I_{load,\min}$ with $I_{load,min}$=3A. The ripple increases with t_{on}, but also with V_d, so check both combinations:
V_d=43.2V and D=0.5: $L_{min,1}$=4.17μH
V_d=52.8V and D=0.408 $L_{min,2}$=4.93μH, so use L=4.93μH

4.1 $m_a = \frac{\hat{v}_{control}}{\hat{v}_{tri}}$; $V_0\sqrt{2} = m_a \cdot V_d$

4.2 $\mathbf{I}_0$ = 1000/230 = 4.35A
$\mathbf{V}_L = j\omega L \mathbf{I}_0$ = j 20.5 V
$\mathbf{V}_0 = \mathbf{E}_0 + j\omega L \mathbf{I}_0$

$$V_0 = \sqrt{230^2 + 20.5^2} = 230.9 \quad V$$

$$m_a = \frac{V_0\sqrt{2}}{V_d} = \frac{230.9\sqrt{2}}{350} = 0.933$$

$$\varphi = \arctan(\frac{V_L}{E_a}) = \arctan(\frac{20.5}{230}) = 5.09 \quad \text{deg}$$ (v_c leading to e_a)

4.3 $$V_{d,\min} = \frac{V_0\sqrt{2}}{m_{a,\max}} = \frac{230.9\sqrt{2}}{1} = 326.5 \quad V$$

Exam *Electronic Power Conversion* 20 March 2002

(30) PROBLEM 1

Given is a single-phase rectifier as shown in Fig. 9 with L_s=2 mH
The supply voltage v_s is sinusoidal with amplitude 230√2 V and frequency 50Hz.

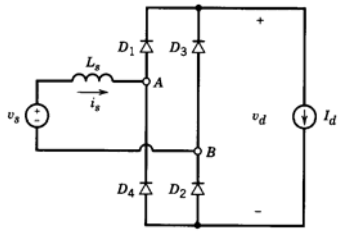
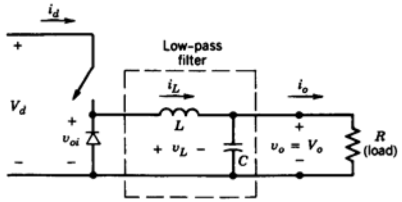


Fig. 9

(10) 1.1 Sketch v_s, v_d and i_s as a function of time for I_d=10A.
(10) 1.2 Calculate the commutation angle u as a function of I_d.
(10) 1.3 Give a formula for Vd and Pd as a function of Id, where Vd is the average of v_d and P_d is the average of the output power p_d.

(30) PROBLEM 2

In a step-down converter, consider all components to be ideal.



The output voltage $v_0 \approx V_0$ is held at 5V by controlling the switch duty ratio D.

(15) 2.1 Calculate the minimum inductance L to keep the converter operating in a continuous conduction mode under all conditions V_d= 10 …40V, $P_0 \geq$ 5W and f_s= 50 kHz .
(15) 2.2 Calculate the peak-to-peak ripple ΔV_0 if V_d=12.6 V and I_0=200 mA, where f_s=20 kHz, L=1 mH and C=470 μF.

(40) PROBLEM 3

In Fig. 10a a single-line diagram of a three-phase grid is shown with a utility source (dashed block) and a power electronic load. The power electronic load represents a large industrial three-phase diode rectifier as shown in Fig. 10b.

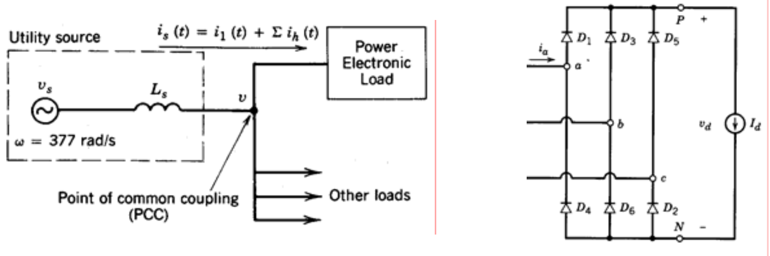


Fig. 10

The utility source (dashed block) is three phase grid with sinusoidal voltage sources v_s in series with inductances L_s . The nominal rms value of the phase voltage is V_s=230V (per phase) and its frequency is f_s=60 Hz.
The load of the rectifier is represented by a constant DC current source I_d.

(10) 3.1 Sketch i_a and calculate the harmonics of the input current ia as a function of I_d, where L_s=0. Assume Ls=0 for this question only.
(10) 3.2 Calculate the average rectifier output voltage V_d as a function of V_s, L_s and I_d. For the next questions L_s=3mH.
(10) 3.3 Describe qualitatively the effect of $L_s \neq 0$ instead of L_s=0 on the input current harmonics. Consider both high-order harmonics and low-order harmonics.

According to local regulations of the utility company, the maximum allowable fifth harmonic voltage at PCC caused by any load should be less than 3% of the nominal voltage (L_s=3 mH).

You may assume for this case that the rms value of the fifth harmonic of the rectifier current is equal to I_{s5} = 0.15 I_d

(10) 3.4 Calculate the maximum allowable value of I_d .

Summary of answers to exam *Electronic Power Conversion* dd 20 March 2002

1.1 See book fig 5.14
1.2 See book eq. 5-30 to 5-32
1.3 See book eq. 5-9, 5-10 and 5-31 to 5-33

2.2 The boundary is first reached at the highest input voltage (lowest D). At V_d=40V: D=0.125.
See book fig. 7-6, eq. 7-5, 7-18 and 7-19; $L = \dfrac{D(V_d - V_0)}{2 f_s I_0} = 43.75\ \mu H$

2.2 See book 7-22 to 7-25 ; $\Delta V_0 = \dfrac{D(1-D)V_d}{8LCf_s^2} = 2.0\ mV$

3.1 See book fig. 5-33, eq. 5-60 to 5-71
3.2 See book eq. 5-86. Note that the phase voltage V_S is given and that $V_{LL} = \sqrt{3}\ V_S$; V_d=538-1,8 I_d
3.3 All harmonics are more or less reduced, including the fundamental. Higher harmonics are attenuated more than the lower harmonics, because steep edges on currents are removed . Lower harmonics are only slightly affected.
3.4 See book eq. 18-2; $5\omega L_s \cdot 0.15 I_d < 0.03\ V_s$ or $I_d < 8.13A$

Exam *Electronic Power Conversion* 10 January 2003

(25) PROBLEM 1

Consider the resistive switching circuit shown in Fig. 11 with V_d=300 V, f_s=100kHz and R=75 Ohm. The switch turn-on time is t_{on} =150 ns and the switch turn-off time is t_{off}=300 ns. Assume linear voltage and current switching characteristics.

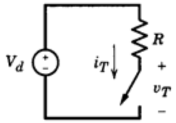


Fig. 11

(10) 1.1 Sketch the waveforms of v_T and i_T and the power p_T that is dissipated in the switch as a function of time.
(10) 1.2 Calculate and plot the average switching power loss as a function of frequency in the frequency range 25 kHz-100 kHz.
(5) 1.3 Calculate the efficiency η of the power transfer from the source V_d to the load R at 100 kHz and a duty ratio D=0.5.

(40) PROBLEM 2

The single-phase rectifier circuit as shown in Fig. 12a is connected to a sinusoidal supply voltage with V_s=120V at 60 Hz. Further L_s=1 mH and V_d=150 V.

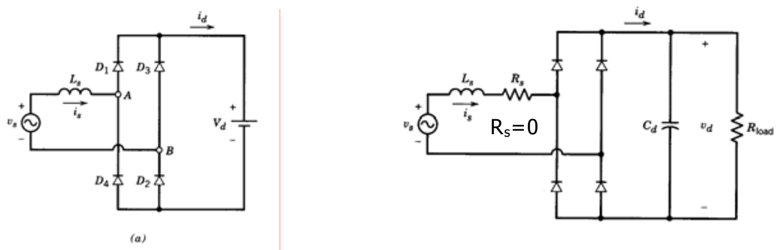


Fig. 12 ***(b)*** .

(10) 2.1 Sketch the waveforms of i_d, i_s, $|v_S|$ and v_L.
(10) 2.2 Calculate by approximation the time instants where relevant voltage intersections occur in the sketch.
(10) 2.3 Calculate the average of current i_d. (difficult if θf is unknown)

The voltage source V_d is replaced by a large capacitor in parallel with a resistor as shown in Fig. 12b. The capacitor is so large that the voltage v_d is constant ($R_{load}C_d$>> 10 ms). The value of the load resistor should be chosen such that V_d=150V again. Assume R_s=0.

(5) 2.4 Calculate the value of R_{load}.
(5) 2.5 To what limit will V_d rise if R_{load} is gradually increased.

(35) PROBLEM 3

For a certain application a dc voltage has to be stepped up from a source voltage V_s to a higher load voltage V_0. The voltage across the load should be fairly constant. The circuit as shown in Fig. 13 is available, however the circuit is not complete yet and at least an inductor L has to be added. The indicated terminals are not necessarily the terminals that have to be used as input and output.

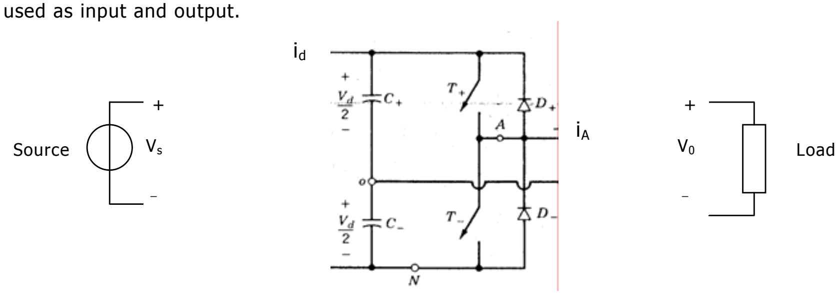


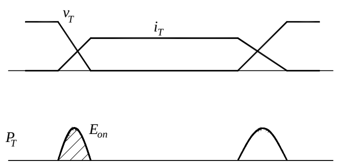
Fig. 13

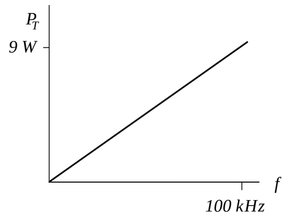
The following is specified:
V_s=150V, V_0=240V, f_s=20 kHz and C_+=C_-= 4700μF and P_0=500W. Inductor L=600μH.

(10) 3.1 Show by means of a circuit diagram how the desired conversion can be obtained by using the circuit from Fig. 13. Show where the inductor L should be added and include the connections to source and load. Describe shortly how the circuit is operated.
(5) 3.2 Express V_o in the duty ratio D and V_s . Define and calculate the duty ratio D.
(10) 3.3 Calculate the average inductor current. Sketch for L=4μH the terminal current i_A the diode current i_{D+} and the voltage v_{AN} or v_{A0}
(10) 3.4 Can i_A have zero crossings? Calculate the minimum value of the inductor that will assure that i_A does not have zero crossings for the given conditions.

Summary of answers to exam *Electronic Power Conversion* dd 10 January 2003

1.1 Note that the waveforms for the switching of resistive loads are quite different from the waveforms for clamped inductive loads (Mohan Fig 2-6). With the circuit from the exam v_T and i_T are always related by: $V_T = V_d - I_T R$. During turn on: $i_T=I_d\, t/t_{on}$ and $v_T=V_d(1-t/t_{on})$; $p_T(t)=v_T\, i_T = V_d\, I_d\, t/t_{on}(1-t/t_{on})$.
Similar during turn off.





1.2 Dissipated energy during turn on: $E_{T,on} = \int_0^{ton} i_T v_T\, dt = V_d I_d \left(\frac{1}{2}\frac{t^2}{t_{on}} - \frac{1}{3}\frac{t^3}{t_{on}^2}\right) = \frac{V_d I_d}{6} t_{on}$ =300*4*1/6*150 ns (J)
Similar for turn off.
Average power: $P_T = \frac{V_d I_d}{6}(t_{on}+t_{off})/T_s$ =200 * (150+300) * 10^{-9} * f_s.

1.3 $\eta = \frac{P_R}{P_d} = \frac{P_d - P_T}{P_d} = \frac{DV_d I_d - P_T}{DV_d I_d} = \frac{600-9}{600} = 0.985$

2.1 See Mohan Fig 5-16

2.2 $\theta_b = \arcsin\left(\frac{V_d}{\sqrt{2}V_s}\right)$ =1.083 rad ; $\theta_p = \pi - \theta_b$ = 2.057 rad

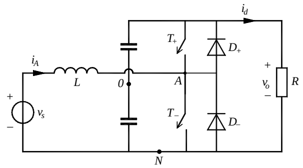
$\int_{\theta_b}^{\theta_f}(V_d - \sqrt{2}V_s \sin\omega t)\,d\omega t = 0$ ➔ $\cos\theta_f + 0.884\cdot\theta_f = 1.426$ ➔ θ_f=2.53 rad

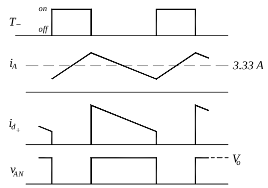
2.3 $i_d = \frac{1}{\omega L_s}\int_{\theta_b}^{\omega t}(\sqrt{2}V_s \sin\omega t - V_d)\,d\omega t = \frac{1}{\omega L_s}(169.7\cos\omega t - 150\omega t)$; $I_d = \frac{1}{\pi}\int_0^{\pi} i_d\, d\omega t$ =2.64A

2.4 I_d=2.64A ; R = V_d/I_d=56.8 Ohm

2.5 $V_{d,max}$=120√2=169.7 V

3.1 The circuit should be configured such that a boost converter is obtained (Mohan section 7-4 and Fig 7-33). T_ and D+ are the active components. Note that the terminal pair {A ,O} cannot be used as input as the node 0 cannot absorb a DC current. The capacitors C+ , C- are in parallel to the load as is required in a boost converter. When T_ is ON the current through L increases and when T_ is OFF the inductor current is 'pushed' in the output circuit via D+.





3.2 $V_0 = \frac{1}{1-D}V_s$ with D=T_{on}/T_s where T_{on} is the on-time of T_ and $T_s=1/f_s$; D=0.375

3.3 I_A=500/150=3.33A ; I_d=500/240=2.08A ; R=500/2.08=115 Ohm ; $i_{A,pp} = \frac{DT_S}{L}V_s$ = 4.72 A

3.4 I_A can have zero crossings if L is small. In that case T+ conducts during the negative part of I_A. The condition for not having zero crossing is similar to the condition for continuous conduction mode with up-converters (see Mohan eq. 7-28). $L_{min} = \frac{DT_S}{\hat{I}_A}V_s = \frac{DT_S}{2I_A}V_s$ = 422μH
Note that RC>>T_s, so that V_d is indeed constant.

Exam *Electronic Power Conversion* 11 June 2003

(20) PROBLEM 1

At the terminals of a converter the voltage and current are as shown in Fig. 14.

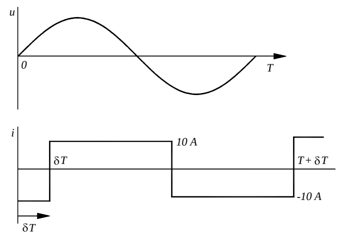


Fig. 14

The amplitude of the voltage is 230√2 V.
(5) 1.1 Calculate the power at the terminals.
(5) 1.2 Calculate the rms value of the current i.
(5) 1.3 Define and calculate the power factor PF.
(5) 1.4 Define and calculate the Distortion Power Factor DPF.

(40) PROBLEM 2

Given is a full-bridge dc-dc converter (H-bridge) with dc motor load as shown (Fig. 15). The motor is modelled by the series connection of R_a, L_a and e_a. For control of the switches so called bipolar voltage switching is applied, where the control signals are obtained by comparing a control signal $v_{control}$ with a triangular waveform v_{tri} .

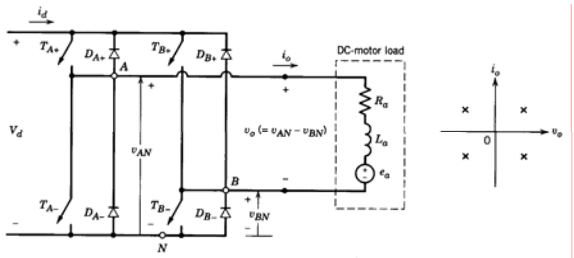


Fig. 15

The following is given:

T_s = 1 ms (T_s is the period of triangular waveform)
R_a = 0.1 Ohm
L_a = 2 mH
V_d = 300V
e_a = 120 V

For the calculation of the current waveform, the resistance R_a can be neglected.

(5) 2.1 Express the average value of v_o in V_d and $v_{control} / \hat{v}_{tri}$.
(5) 2.2 Calculate the required ratio of $v_{control} / \hat{v}_{tri}$ to maintain an average output current of I_0=+10A at e_a = +120 V.
(5) 2.3 Calculate the required ratio of $v_{control} / \hat{v}_{tri}$ to maintain an average output current of I_0= -10A at e_a = +120 V.
(15) 2.4 Sketch the $v_0(t)$, $i_0(t)$ and the source current i_d for I_0 = +10A at e_a = +120 V.
(10) 2.5 Indicate in this sketch which switches are conducting at what time.

(40) PROBLEM 3

For a certain application a dc voltage has to be stepped up from a source voltage V_s to a higher load voltage V_0. The voltage across the load should be fairly constant. The circuit as shown in Fig. 16 is available, however the circuit is not complete yet and at least an inductor L has to be added. The indicated terminals are not necessarily the terminals that have to be used as input and output.

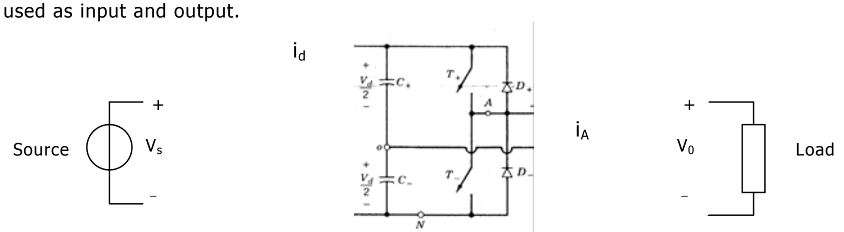


Fig. 16

The following is specified:
V_s=150V, V_0=240V, f_s=20 kHz and C_+=C_-= 4700µF and P_0=500W.
Inductor L=600µH.

(5) 3.1 What type of converter would you preferably use for this conversion?

(10) 3.2 Show by means of a circuit diagram how the desired conversion can be obtained by using the circuit from Fig. 16. Show where the inductor L should be added and include the connections to source and load. Describe shortly how the circuit is operated.
(5) 3.3 Express V_o in the duty ratio D and V_s . Define and calculate the duty ratio D.
(10) 3.4 Calculate the average inductor current. Sketch for L=600µH the terminal current i_A , the diode current i_{D+} and the voltage v_{AN} or v_{A0}
(10) 3.5 Can i_A have zero crossings? Calculate the minimum value of the inductor L that will assure that i_A does not have zero crossings for the given conditions.

Summary of answers to exam *Electronic Power Conversion* dd 11 June 2003

1.1 $P = \frac{1}{T}\int_0^T u\, i\, dt = \frac{2 \cdot 230\sqrt{2} \cdot 10}{\pi} \cdot \cos 2\pi\delta = 2070 \cos \pi\delta \quad W$

1.2 $I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2 dt} = 10\ A$

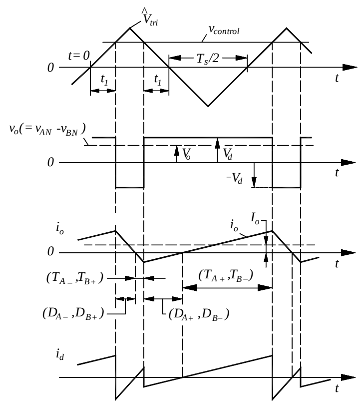
1.3 $PF = \frac{P}{U_{rms} I_{rms}} = \frac{2\sqrt{2}}{\pi} \cos 2\pi\delta = 0.9 \cos 2\pi\delta$

1.4 $DPF = \frac{I_{1,rms}}{I_{rms}} = \frac{10 \cdot 2\sqrt{2}/\pi}{10} = 0.9$ (Note that for a sinusoidal voltage: PF=DPF. cosφ)

2.1 $V_0 = V_d \frac{v_{control}}{\hat{v}_{tri}}$

2.2 $v_o(t) + v_R(t) + v_L(t) - e_a(t) = 0$
After averaging: $V_0 + I_0 R - e_a = 0$
Or: $300 \frac{v_{control}}{\hat{v}_{tri}} + 10 \cdot R - 120 = 0$ so: $\frac{v_{control}}{\hat{v}_{tri}} = \frac{121}{300} = 0.403$; (D_1=0.702)

2.3 $\frac{v_{control}}{\hat{v}_{tri}} = \frac{119}{300} = 0.397$



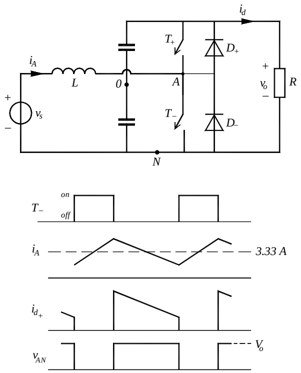
I_0=10A

$$\Delta I_0 = \frac{(V_d - e_0) D_1 T_s}{L_a} = \frac{300 - 120}{2 \cdot 10^{-3}} 0.702 \cdot 10^{-3} = 6$$

positive peak current: 10 + 63/2 = 41.6 A
negative peak current: 10 - 63/2 = -21.6 A

2.4 Like Mohan fig. 7-29e

3.1 Boost converter (Mohan section 7-4 and Fig 7-33).
3.2 The circuit should be configured such that a boost converter is obtained (Mohan section 7-4 and Fig 7-33). T_ and D+ are the active components. Note that the terminal pair {A ,O} cannot be used as input as the node 0 cannot absorb a DC current. The capacitors C+ , C- are in parallel to the load as is required in a boost converter. When T_ is ON the current through L increases and when T_ is OFF the inductor current is 'pushed' in the output circuit via D+.



3.3 $V_0 = \dfrac{1}{1-D} V_s$ with D=T_{on}/T_s where T_{on} is the on-time of T_ and $T_s=1/f_s$; D=0.375

3.4 I_A=500/150=3.33A ; I_d=500/240=2.08A ; R=500/2.08=115 Ohm ; peak-to-peak value of the current: $i_{A,pp} = \dfrac{DT_S}{L} V_s$ = 4.72 A

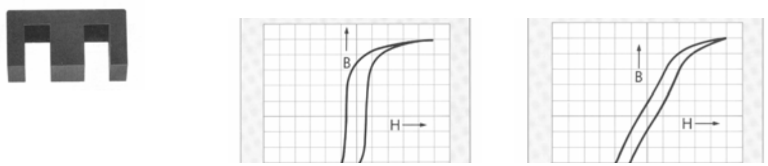
3.5 I_A can have zero crossings if L is small. In that case T+ conducts during the negative part of I_A. The condition for not having zero crossing is similar to the condition for continuous conduction mode with up-converters (see Mohan eq. 7-28). $L_{min} = \dfrac{DT_S}{\hat{I}_A} V_s = \dfrac{DT_S}{2I_A} V_s$ = 422μH

Note that RC>>T_s, so that V_d is indeed constant.

Exam *Electronic Power Conversion* 9 January 2004 (selection)

(30) PROBLEM 1

For a forward converter a transformer is needed. For the transformer two pairs of so-called E-cores with identical shape are available (Fig. 17a), but they are made from different materials. The basic BH-loop of the respective materials are shown in Fig. 17b and c for the case of maximum excitation of the material. Only a part of the BH-loop will be used. Both the primary, the secondary and the auxiliary demagnetising winding of the forward converter are wound around the central leg. The turns ratio between primary and demagnetisation winding is 1.



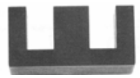


Fig. 17 a: double E-core; b: normal BH-loop; c: flat BH-loop.
For diagrams a and b: B-scale: 0.1 T per division; H-scale: 5 A/m per division

The E-cores have the following data:
A_c = 1 cm2 Core cross section of central leg
l_e = 4 cm Equivalent length of magnetic path of field lines
Other relevant material properties (B_s, B_r, H_c) can be read from the figure.
For the forward converter the following is given:
f_s = 75 kHz (switching frequency)
V_d = 300 V (supply voltage)

(10) 1.1 What type of material (normal loop or flat loop) is most suited for the application and why.
What do you choose as the operating range in the loop (more answers are possible)?
(10) 1.2 Calculate the minimum number of turns $N_{1,min}$ for the selected type of material to avoid saturation. Read relevant data from Fig. 17. Sketch the flux density B as a function of time for D=0.5 and indicate minimum and maximum values.
(10) 1.3 Estimate the magnetizing inductance L_m for $N_1=N_{1,min}$ (20% accuracy is sufficient here).
1.4 Calculate the peak value of the current in the auxiliary winding.

(40) PROBLEM 3

Given is a single-phase H bridge dc/ac voltage source converter that is connected to a single phase induction motor with counter emf e_0, as shown in Fig. 18.

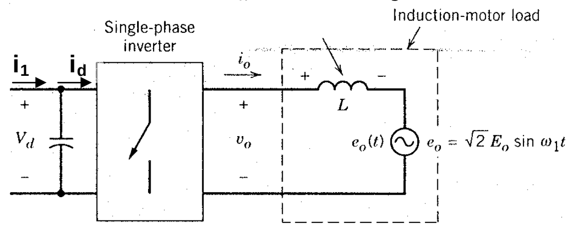


Fig. 18

The output voltage v_0 of the inverter is obtained by bipolar voltage switching similar to Fig. 19. To obtain a low distortion linear modulation is applied (no overmodulation; m_a<1).

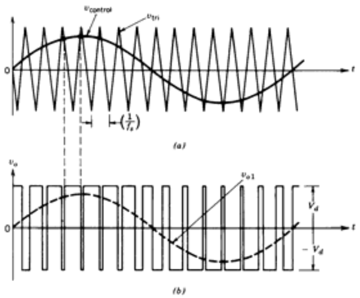


Fig. 19 (actual switching frequency is much higher than shown here)

Given is further:

V_d = 350V	(DC link voltage)
ω_1	(fundamental frequency of v_o and e_0)
$\omega_{1,nom}$ =2π60 rad/s	(nominal value of ω_1)
$V_{01,nom}$ =230 V	(nominal rms value of fundamental of v_0)
e_0	(counter emf which is sinusoidal)
L = 30 mH	(inductance of machine)
f_s=7.5 kHz	(frequency of triangular carrier v_{tri})
C_d=1 mF	(capacitance of input filter)

At nominal speed and nominal voltage the input power of the loaded drive is 1 kW at cos ϕ_1=0.8

(10) 3.1 Sketch equivalent circuit models to calculate the fundamental component of the current i_0 and the ripple component of the current i_0. Calculate an upper limit for the peak-to-peak current ripple in i_o that is caused by the switching.

(10) 3.2 Calculate the rms value of the fundamental of i_0 when the machine runs at rated speed and rated power. Sketch a phasor diagram with the phasors of e_0, v_0 and i_0.

(5) 3.3 Define the modulation ratio m_a and give the relation between V_{o1}, m_a and V_d, where V_{o1} is the rms value of the fundamental of the output voltage. Calculate the modulation ratio m_a such that the machine runs at nominal speed and nominal voltage.

(10) 3.4 Sketch the instantaneous power $p_0(t)$ that is transmitted by the fundamental current i_0 and voltage v_0
(Note: $2\sin\omega t\cdot\sin(\omega t-\phi)=\cos\phi-\cos(2\omega t-\phi)$)

(5) 3.5 Calculate the low-frequency (<1 kHz) peak-to-peak voltage ripple ΔV_d, assuming that the current i_1 is constant.

Summary of answers to exam *Electronic Power Conversion* dd 9 January 2004

1.1 For a given core the ideal loop would be very steep with a large difference between B_s and B_r. On one hand a steep loop results in a small magnetising current resulting in less losses, although in general the losses caused by the magnetising current is small in comparison to the transformed load current (N1/N2 i2). On the other hand the number of turns depends on the available flux swing. For a forward converter the flux swing is B_s-B_r because of the unipolar excitation. The answer is that the flat core is preferred because of the much larger flux swing, resulting is less turns and less losses. Select B_{max}=+0.4 to have some margin to saturation. B_r=+0.1

1.2 $\Delta B\,N_1\,A_c=\int_0^{DT_s}v_1dt$ or $N_1=\dfrac{DV_d}{f_sA_c(B_s-B_r)}=\dfrac{0.5\cdot300}{75\cdot10^3\cdot10^{-4}(0.4-0.1)}=67$

1.3 $L_m=\dfrac{\mu N^2A_c}{l_e}$ (this follows from eq. 3-60 and 3-80) where μ is obtained from the BH-loop: μ = B/H ≈ 0.5/20=0.025; $L_m=\dfrac{0.025\cdot67^2\cdot10^{-4}}{0.04}=280\,mH$

1.4 Because N_1=N_3, the peak value of the current in the auxiliary winding is equal to the peak value of the magnetising current.

$$\hat{i}_m=\frac{1}{L_c}\int_0^{DT_s}V_d\,dt=\frac{300\cdot0.5}{75\cdot10^3\cdot280\cdot10^{-3}}=7.1\,mA$$

Another way:

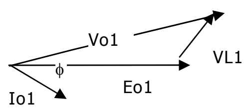
$$\hat{H}\,l=N\,\hat{i}_m\quad or\quad \hat{i}_m=\frac{\hat{H}\,l}{N}=\frac{12.5\cdot0.04}{67}=7.4mA$$

3.1 See Mohan fig. 8-18 b and c. Because the circuit is linear, the fundamental and ripple component can be treated separately: $v_1=v_{01}+v_{ripple}$ and $i_1=i_{01}+i_{ripple}$. The (sinusoidal) fundamental component follows from the phasor equation: $\vec{V}_{01}=\vec{E}_0+\vec{V}_{L1}=E_0+j\omega LI_{01}$. The ripple follows from: $i_{0,ripple}(t)=\dfrac{1}{L}\int_0^t v_{0,ripple}(\varsigma)d\varsigma$.

The largest ripple occurs during the zero crossing of $v_{01}(t)$ (see fig 8-19b). Then the amplitude of the ripple voltage is $V_d/2$ and the duration of the pulse is $T_s/2$. The maximum amplitude of the current equals:

$$\Delta i_0=\frac{V_d/2}{2f_s\cdot L_s}=\frac{350/2}{2\cdot7.5\cdot10^3\cdot30\cdot10^{-3}}=0.38A$$

3.2 $P_0=V_0I_0\cos\phi_1$ or I_0=5.43 A . (so ωL_s I_0=61.4V). Note that ϕ is the angle between V_o and I_o. The phasor diagram is like fig 8-18d.



3.3 $m_a=\dfrac{\hat{v}_{control}}{\hat{v}_{tri}}$; $V_0\sqrt{2}=m_a\cdot V_d$ or m_a =0.929.

3.4 $p_0(t)=\sqrt{2}V_0\sin\omega_1t\cdot\sqrt{2}I_0\sin(\omega_1t-\phi)=V_0I_0\cos\phi-V_0I_0\cos(2\omega_1t-\phi)$.

3.5 For low frequencies: $p_d(t)=p_0(t)$ with $p_d(t)=V_d\cdot i_d$ (See Mohan fig 8-13) so

$$i_d(t)=\frac{V_0I_0}{V_d}\cos\phi-\frac{V_0I_0}{V_d}\cos(2\omega_1t-\phi)=2.85-3.57\cos(\omega_1t-36.9^0)$$

Amplitude of (sinusoidal) low frequency (120 Hz) current ripple:

$$\hat{i}_{ripple}=\frac{V_0I_0}{V_d}=\frac{230\cdot5.43}{350}=3.57A;\quad\Rightarrow\quad \hat{V}_{d,ripple}=\frac{\hat{i}_{ripple}}{2\omega_1C_d}=\frac{3.57}{2\cdot120\pi\cdot10^{-3}}=4.73V;$$

Peak-to-peak value: $\Delta V_d=2\hat{V}_{d,ripple}=9.46V$

Exam *Electronic Power Conversion* 9 June 2004

(40) PROBLEM 1

A forward converter with demagnetisation winding as shown in Fig. 20 is to be designed with the following specifications:

V_d = 150V and 300V
V_0 =5V (regulated)
f_s = 100 kHz
P_{load} = 200W
L = 2 μF
C_0=1000 μF

The converter should be able to operate at both input voltages.
The converter should operate in continuous conduction mode for all operational conditions.
The winding N_3 serves complete demagnetization of the magnetization inductance of the core.
The converter should be designed to operate with a maximum duty ratio D_{max} of 0.7.
Assume all components to be ideal except for the presence of the magnetising inductance of the transformer.

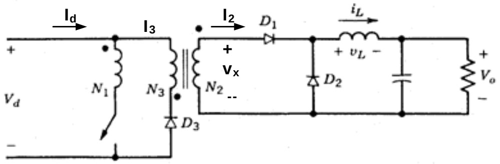


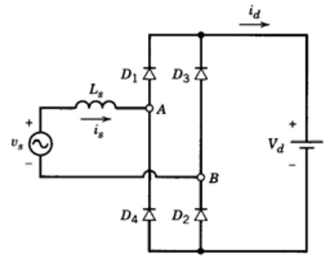
Fig. 20

(10) 1.1 Calculate the winding ratio N_3/N_1 such that D_{max} < 0.7
(5) 1.2 Calculate N_2/N_1 if this turns ratio is desired to be as small as possible.
(10) 1.3 Sketch v_x , i_L and v_L for V_d=150V. Indicate values in the sketch of v_x and i_L.
(5) 1.4 Calculate the maximum voltage that is applied to the switch for any of the operational conditions.
(10) 1.5 Calculate the peak-to-peak value of the ripple in the output voltage for V_d=300V

(30) PROBLEM 2

Given is a single-phase rectifier, as shown in Fig. 21a, that is connected to a block shaped supply voltage v_s (Fig. 21b) and a constant load voltage V_d:
Given is:

V_d=240V
V_s=300V (amplitude of v_s as shown in Fig. 21b)
f_s= 50Hz (frequency of v_s)
L_s=2 mH



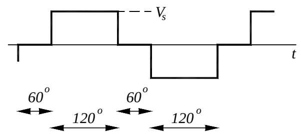


Fig. 21a **Fig. b**

(10) 2.1 Sketch v_L, i_d and i_s as a function of time.
(5) 2.2 Calculate the peak value if i_d.
(5) 2.3 Calculate the average current I_d and the average output power P_d.
(10) 2.4 What is the range of V_d for discontinuous conduction of i_s.

(30) PROBLEM 3

Given is a bi-directional single-phase dc/ac converter that is connected to a grid with voltage e_0, as shown in Fig. 22.

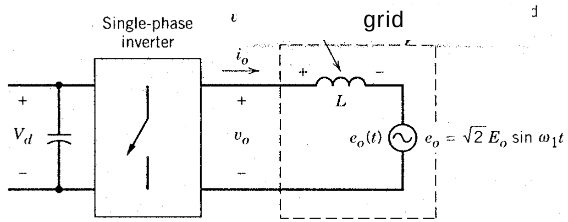


Fig. 22

The output voltage v_0 of the inverter, that contains a full-bridge voltage source converter, is obtained by bipolar voltage switching as shown in Fig. 31. Only linear modulation is applied (no overmodulation).

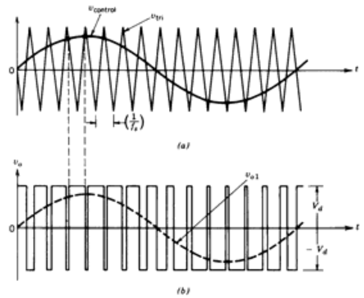


Fig. 23 (Note: actual switching frequency is much higher than shown here)

Given is further: V_d = 350V

$e_0 = E_0\sqrt{2}\sin\omega_1 t$ with E_0 = 230V and $\omega_1 = 2\pi 50$
L = 15 mH
f_s = 7.5 kHz (frequency of triangular carrier v_{tri})

The inverter is fed from a photovoltaic array and the objective is to supply power to the grid at unity power factor. In the following questions the ripple that is caused by the switching can be neglected.

(5) 3.1 Sketch equivalent circuit models to calculate the fundamental component of the current i_0 and the ripple component of the current i_0.

(5) 3.2 Define the modulation ratio m_a and give the relation between V_o, m_a and V_d, where V_o is the rms fundamental of the output voltage.

(10) 3.3 Calculate the modulation ratio m_a such that 1 kW is supplied to the grid at unity power factor (pf=1) in e_0. Sketch the associated phasor diagram with the phasors of e_0, v_0 and i_0.

(5) 3.4 What is the lowest value of V_d where we can still supply 1 kW to the grid with linear sinusoidal modulation?

(5) 3.5 Calculate an upper limit for the peak-to-peak current ripple in i_o that is caused by the switching.

Summary of answers to exam *Electronic Power Conversion* dd 9 June 2004

1.1 upflux=downflux so $\frac{V_d}{N_1}DT_s = \frac{V_d}{N_3}(1-D)T_s$ so $\frac{N_3}{N_1} = \frac{1-D}{D} = 0.43$

1.2 $V_0 = \frac{N_2}{N_1}DV_d$ with D_{max}=0.7 for V_d=150V; $\frac{N_2}{N_1} > \frac{V_o}{V_{d,\min}D_{\max}} = \frac{5}{150\cdot 0.7} = 0.0476$

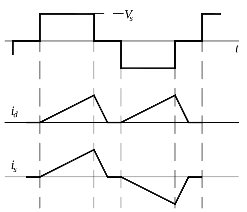
Note: if you combine D_{max} with V_{dmax}, (leading to N_2/N_1=0.0238) than the converter cannot be operated at 150V.

1.3 See Mohan.

1.4 $V_{sw} = V_d + \frac{N_1}{N_3}V_d = 300\cdot(1+1/0.43) = 998V$

1.5 $V_{pp} = \frac{\Delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\Delta i_L}{2}\frac{T_s}{2}$ with $\Delta i_L = \frac{(1-D)T_s V_0}{L}$

$\frac{V_{pp}}{V_0} = \frac{1}{8}\frac{T_s^2(1-D)}{LC} = \frac{10^{-10}\cdot(1-0.35)}{8\cdot 2\cdot 10^{-6}\cdot 10^{-3}} = 0.0041$; V_{pp} = 20 mV



2.2 $I_{peak} = \frac{1}{L_s}\int_0^{6,67ms}(V_s - V_d)\,dt = 200A$

2.3 $I_d = \frac{1}{T}\int_0^T i_d dt = \frac{2\cdot 150^o\cdot 200/2}{360^o}$ = 83.33 A; $P_d = \frac{1}{T}\int_0^T V_d\ i_d dt = \frac{1}{T}V_d\int_0^T i_d dt = 20\ \ kW$

2.4 $\Delta i_{d,up} = \Delta i_{d,down}$; i_d should be zero again before t=T_s/2 so $(V_0 - V_d)\cdot 6.67ms < V_d\cdot 3.33ms$ or V_d > 200 V

3.1 See Mohan fig 8-18 b and c.

3.2 $m_a = \frac{\hat{v}_{control}}{\hat{v}_{tri}}$; $V_0\sqrt{2} = m_a\cdot V_d$

3.3 $\mathbf{I}_0$ = 1000/230 = 4.35A
$\mathbf{V}_L = j\omega L\mathbf{I}_0$ = j 20.5 V
$\mathbf{V}_0 = \mathbf{E}_0 + j\omega L\mathbf{I}_0$

$$V_0 = \sqrt{230^2 + 20.5^2} = 230.9\quad V$$

$$m_a = \frac{V_0\sqrt{2}}{V_d} = \frac{230.9\sqrt{2}}{350} = 0.933$$

$$\varphi = \arctan\left(\frac{V_L}{E_a}\right) = \arctan\left(\frac{20.5}{230}\right) = 5.09\quad \text{deg}$$ (v_c leading to e_a)

3.4 $V_{d,\min} = \frac{V_0\sqrt{2}}{m_{a,\max}} = \frac{230.9\sqrt{2}}{1} = 326.5\quad V$

3.5 The ripple follows from: $i_{0,ripple}(t) = \frac{1}{L}\int_0^t v_{0,ripple}(\varsigma)d\varsigma$.

The largest ripple occurs during the zero crossing of v_{01}(t) (see fig 8-19b). Then the amplitude of the ripple voltage is V_d/2 and the duration of the pulse is T_s/2:

$$\Delta i_0 = \frac{1}{L_s}\int_0^{T_s/2}V_d dt = \frac{V_d/2}{2f_s\cdot L_s} = \frac{350/2}{2\cdot 7.5\cdot 10^3\cdot 15\cdot 10^{-3}} = 0.78A$$

Exam *Electronic Power Conversion* 21 January 2005

(20) PROBLEM 1

Given is a switch-mode DC-power supply, where the output voltage v_o should be regulated close to its nominal value. For that purpose a negative-feedback control system is used to reduce the effect of variations in the input voltage v_d and the load.

(5) 1.1 Sketch a block diagram of the system, and describe shortly the function of the blocks. Indicate all relevant variables in the diagram.

(10) 1.2 Describe shortly the steps that are needed to obtain the small-signal transfer function $\tilde{v}_0(s)/\tilde{d}(s)$ of the system. Here v_0 is the output voltage and d is the duty ratio. Note that you are not expected to calculate the transfer function.

(5) 1.3 Obtain an averaged state-space description of an up-converter (result of step 2).

(40) PROBLEM 2

Given is a flyback converter as shown in Fig. 24b. The load resistance R_0 may vary and the output voltage V_0 should be kept constant by adapting the duty ratio D. The converter may operate both in continuous and discontinuous conduction mode.

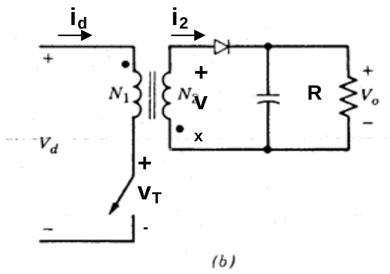


Fig. 24 Flyback converter

The following is given:

f_s = 100 kHz (switching frequency)
R_0 = 0.5 ..100 Ohm (range of load resistance)
L_{m2} = 2 μH (magnetizing inductance, seen from secondary side)
V_d = 300V (supply voltage)
V_0 = 5V (required output voltage)
C_0 = 100 μF (output filter capacitor)
N_1/N_2 = 80 (turns ratio)

(10) 2.1 Derive the voltage transfer function V_0/V_d in continuous conduction mode (incomplete demagnetisation mode) as a function of the duty ratio D and other relevant circuit parameters.

(10) 2.2 What is the range of the load current I_0 for continuous conduction mode (V_0=5V)? (Hint: Consider the course of the current i_2 at the boundary of continuous conduction mode and calculate $\hat{i}_2$).

(5) 2.3 Calculate the required duty ratio D_1 when I_0= 10A (so R_0=0.5 Ohm). (V_0=5V).

(5) 2.4 Calculate the required duty ratio D_2 when I_0= 0.5 A . (V_0=5V). (Hint: $P_0 = f_s \cdot \frac{1}{2} L_{m2} \hat{i}_2^2$ and $P_0 = f_s \cdot \frac{1}{2} L_{m1} \hat{i}_1^2$)

(10) 2.5 Sketch i_d, i_2, v_x and v_T as a function of time for R_0=0.5 Ohm and indicate relevant values.

(40) PROBLEM 2

Given is a full-bridge dc-ac converter (H-bridge) with a single phase ac motor as shown (Fig. 25). The motor is modelled by the series connection of an inductance L_a and the counter emf e_a. For control of the switches so-called bipolar voltage switching is applied, where the ON/OFF signals for the switches are obtained by comparing a sinusoidal control signal $v_{control}$ with a triangular waveform v_{tri} (Fig. 26).
Linear modulation is applied to obtain a low distortion (no overmodulation; m_a<1).

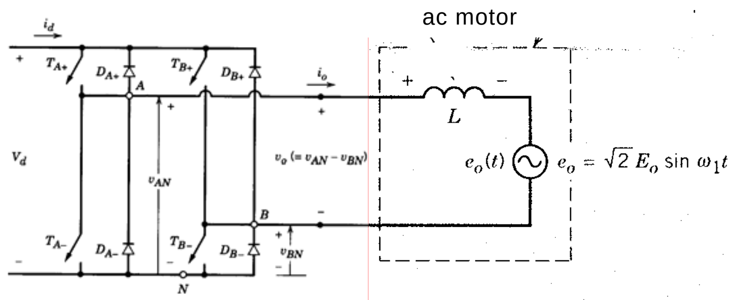


Fig. 25

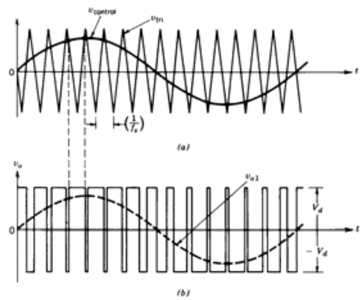


Fig. 26 (Note: the actual switching frequency is much higher than shown here)

Given is further:

V_d = 350V (DC link voltage)
ω_1 (fundamental frequency of the motor voltage v_o and of the counter emf e_0)
$\omega_{1,nom}$ =2π60 rad/s (nominal value of the fundamental frequency of the motor)
$V_{01,nom}$ =230 V (nominal rms value of fundamental of v_0)
e_0 (counter emf which is sinusoidal)
L = 30 mH (inductance of motor)
f_s=7.5 kHz (frequency of triangular carrier v_{tri})

At nominal speed and nominal voltage the input power of the loaded drive is 1 kW at cos ϕ_1=0.8

(5) 3.1 Sketch the equivalent circuit models to calculate the fundamental component of the current i_0 and the ripple component of the current i_0.

(5) 3.2 During what part of the output voltage does the maximum current ripple occur? Calculate an upper limit for the peak-to-peak current ripple in i_0 that is caused by the switching.

(5) 3.3 Calculate the rms value of the fundamental of i_0 when the machine runs at rated speed and rated power.

(10) 3.4 Define the modulation ratio m_a and give the relation between V_{o1}, m_a and V_d, where V_{o1} is the rms value of the fundamental of the output voltage. Calculate the

modulation ratio m_a such that the machine runs at nominal speed and nominal voltage.

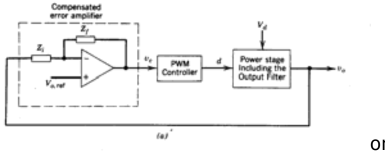
(5) 3.5 Sketch the instantaneous power $p_0(t)$ that is transmitted by the fundamental current i_0 and voltage v_0
(Note: $2\sin\omega t\cdot\sin(\omega t-\phi)=\cos\phi-\cos(2\omega t-\phi)$)

(5) 3.6 Calculate the low-frequency (<1 kHz) peak-to-peak voltage ripple ΔV_d, assuming that the current i_1 is constant.

(5) 3.7 What will change in the answers to problems 3.1 to 3.6 if unipolar switching is used instead of bipolar switching?

Summary of answers to exam *Electronic Power Conversion* dd 21 January 2005

1.1 See Mohan section 10-5.



or similar drawing.

The block on the right side is the power stage with inputs duty ratio d and supply voltage V_d.
The PWM block converts the control signal v_c to the signal d.
The left block is the control block that compares the measured output voltage with some reference and generates the control signal v_c.

1.2 See Mohan section 10-5-1

Step 1 Obtain state-space equations for subsequent subcycles

Step 2: Averaging; Obtain average description of the circuit by averaging the time-weighted state matrices:

Step 3: Linearization; separate the variables in steady state components and small perturburations

Step 4 Laplace transformation to s-domain

1.3 State variables are i_L and v_C

$$\left.\begin{aligned} L\frac{di_L}{dt}&=V_d\\ C\frac{dv_C}{dt}&=-\frac{v_c}{R}\end{aligned}\right\}\quad\text{or}\quad \begin{bmatrix}\frac{di_L}{dt}\\ \frac{dv_c}{dt}\end{bmatrix}=\begin{bmatrix}0 & 0\\ 0 & -\frac{1}{RC}\end{bmatrix}\bullet\begin{bmatrix}i_L\\ v_c\end{bmatrix}+\begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_d \qquad \text{for } 0<t<DT_s$$

$$\left.\begin{aligned} L\frac{di_L}{dt}&=-v_c+V_d\\ C\frac{dv_C}{dt}&=i_L-\frac{v_c}{R}\end{aligned}\right\}\quad\text{or}\quad \begin{bmatrix}\frac{di_L}{dt}\\ \frac{dv_c}{dt}\end{bmatrix}=\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix}\bullet\begin{bmatrix}i_L\\ v_c\end{bmatrix}+\begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_d \qquad \text{for } DT_s<t<T_s$$

Averaged:

$$\begin{bmatrix}\frac{di_L}{dt}\\ \frac{dv_c}{dt}\end{bmatrix}=\begin{bmatrix}0 & -\frac{(1-D)}{L}\\ \frac{(1-D)}{C} & -\frac{1}{RC}\end{bmatrix}\bullet\begin{bmatrix}i_L\\ v_c\end{bmatrix}+\begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_d$$

2.1 Continuous conduction mode: $\frac{V_0}{V_d}=\frac{N_1}{N_2}\frac{D}{1-D}$

2.2 At the boundary of continuous and discontinuous conduction mode the answer from 2.1 is valid, so $D=\frac{V_0}{\frac{N_1}{N_2}V_d+V_0}=0.57$

Note that at the boundary the current i_2 is a triangle that just becomes zero at $t=T_s$.

From Δi_2 when the switch is off : $\hat{i}_{2,boundary}=\frac{V_0}{L_{m2}}(1-D)T_s=10.75A$

From course of i_2 at the boundary it follows: $I_{0,Boundary}=(1-D)\frac{\hat{i}_2}{2}=2.31A$

So the region for continuous conduction mode is $I_0>2.31A$ (or $R_0<2.16$ Ohm)

2.3 The load current is larger than 2.31 A, so we have continuous conduction mode, so $D_1=0.57$

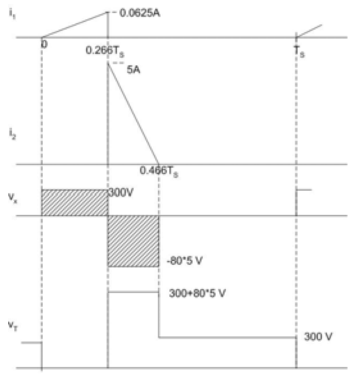
2.4 The load current is smaller than 2.31A , so we have discontinuous conduction mode $P_0=f_s\cdot\frac{1}{2}L_{m2}\hat{i}_2^2$ or $\hat{i}_2=\sqrt{\frac{2P_0}{f_sL_{m2}}}=\sqrt{\frac{2\cdot5\cdot0.5}{10^5\cdot2\cdot10^{-6}}}=5A$ and $\hat{i}_1=\frac{\hat{i}_2}{80}=0.0625A$

Also $\hat{i}_1=\frac{V_d}{L_{m1}}D_2T_s$ or $D_2=\frac{\hat{i}_1L_{m1}}{V_dT_s}=\frac{0.0625\cdot12.8m}{300\cdot10\mu}=0.266$ with

$$L_{m1}=\left(\frac{N_1}{N_2}\right)^2L_{m2}=80^2\cdot2\mu H=12.8mH$$

Note: it is more straightforward to calculate $\hat{i}_1$ directly from $P_0=f_s\cdot\frac{1}{2}L_{m1}\hat{i}_1^2$.

2.5



Duration of i_2:

$$D_{i2}=\frac{\hat{i}_2L_{m2}}{V_0T_s}=\frac{5\cdot2\mu}{5\cdot10\mu}=0.2$$

3.1 See Mohan fig 8-18 b and c.

3.2 The largest ripple occurs during the zero crossing of $v_{01}(t)$ (see fig 8-19b). Then the amplitude of the ripple voltage is V_d and the duration of the pulse is $T_s/2$:

$$\Delta i_0=\frac{1}{L_s}\int_0^{T_s/2}V_d\,dt=\frac{V_d}{2f_s\cdot L_s}=\frac{350}{2\cdot7.5\cdot10^3\cdot30\cdot10^{-3}}=0.78A$$

3.3 $P=V_{01}I_0\cos\varphi$ or $I_0=\frac{P}{V_{01}\cos\varphi}=\frac{1000}{230\cdot0.8}=5.43A$

3.4 $m_a = \frac{\hat{v}_{control}}{\hat{v}_{tri}}$; $V_{01}\sqrt{2} = m_a \cdot V_d$ or $m_a = \frac{V_{01}\sqrt{2}}{V_d} = \frac{230\sqrt{2}}{350} = 0.93$

3.5 $p(t) = v_0(t) \cdot i_0(t) = V_0\sqrt{2}\sin\omega t \cdot I_0\sqrt{2}\sin(\omega t - \phi) = V_0 I_0 \cos\phi - V_0 I_0 \cos(2\omega t - \phi)$

$$= 230 \cdot 5.43 \cdot 0.8 - 230 \cdot 5.43 \cos(2\omega t - \phi)$$
$$= 1000 - 1250\cos(2\omega t - \phi)$$

with $\phi = \arccos 0.8 = 37^0$

The waveform is a sinus with double frequency and average value 1000W, top value 2250V, bottom value –250V and lagging $\phi/2$ behind the voltage.

3.6 For low frequencies: $p_d(t) = p_0(t)$ with $p_d(t) = V_d \cdot i_d$ (See Mohan fig 8-13) so

$$i_d(t) = \frac{V_0 I_0}{V_d}\cos\phi - \frac{V_0 I_0}{V_d}\cos(2\omega_1 t - \phi) = 2.85 - 3.57\cos(\omega_1 t - 36.9^0)$$

Amplitude of (sinusoidal) low frequency (120 Hz) current ripple:

$$\hat{i}_{ripple} = \frac{V_0 I_0}{V_d} = \frac{230 \cdot 5.43}{350} = 3.57A; \quad \rightarrow \quad \hat{V}_{d,ripple} = \frac{\hat{i}_{ripple}}{2\omega_1 C_d} = \frac{3.57}{2 \cdot 120\pi \cdot 10^{-3}} = 4.73V;$$

Peak-to-peak value: $\Delta V_d = 2\hat{V}_{d,ripple} = 9.46V$

3.7 Only the answer to 3.2 will change. The ripple will at least be halved because of the doubled hf-frequency in v_0.

Exam *Electronic Power Conversion* 15 June 2005

(20) PROBLEM 1

Given is a simple circuit with a generic switch as shown in the figure a

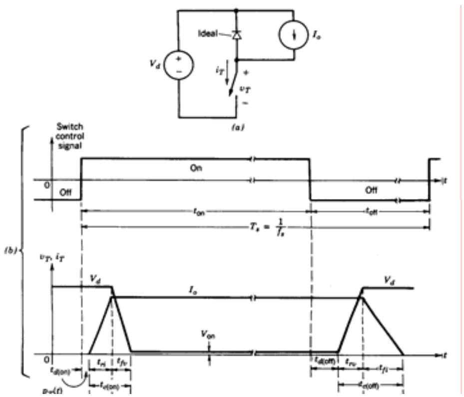


Fig. 27

The data sheet of the switch specifies the following switching times corresponding to the linear switching characteristics as shown in the figure.

t_{ri} = 80 ns ;
t_{fv} = 80 ns ;
t_{rv} = 120 ns ;
t_{fi} = 200 ns

Further: V_d=500V ;

I_0 = 6A.

(5) 1.1 Sketch the instantaneous switching loss as a function of time.

(10) 1.2 Calculate the switching power loss as a function of the switching frequency in a range 25 - 100 kHz, assuming V_d=500V and I_0 = 6A.

(5) 1.3 Calculate and plot the total losses as a function of the switching frequency in a range 25 - 100 kHz in the switch when the on-state voltage is V_{on} =1.5V at 6A and the duty ratio of the switch is D = 0.6 (assume $t_{d(on)}$=$t_{d(off)}$).

(20) PROBLEM 2

At the terminals of a converter the voltage and current are as shown in Fig. 28.

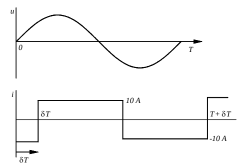


Fig. 28

The amplitude of the voltage is 230√2 V.

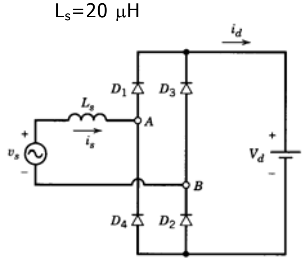
(5) 2.1 Calculate the power at the terminals.
(5) 2.2 Calculate the rms value of the current i.
(5) 2.3 Define and calculate the power factor PF.
(5) 2.4 Define and calculate the Distortion Power Factor DPF.

(30) PROBLEM 3

Given is a single-phase rectifier that is connected to a supply voltage v_s and a battery as shown in Fig. 29a. The battery is represented by a DC load voltage V_d. The voltage v_s has a block-like shape (Fig. 29b) that is produced by some HF inverter (not shown). The rectifier is intended to charge the battery. Depending on the charging state of the battery the voltage V_d may vary.

Given is:

$V_{d,nom}$=240V (nominal voltage of V_d)
V_s=300V (amplitude of v_s as shown in Fig. 29b)
T_s=30μs (period of voltage v_s)
f_s= 1/T_s=33.3 kHz (frequency of v_s)
L_s=20 μH



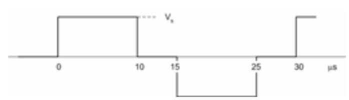


Fig. 29a **Fig. b**

(10) 3.1 Sketch v_L and is as a function of time and indicate relevant values for V_d =$V_{d,nom}$.

(5) 3.2 Calculate the peak value of is, the average current Id and the average output power P_d for $V_d = V_{d,nom}$.
(10) 3.3 What is the range of V_d for discontinuous conduction of i_d in a steady state.
(5) 3.4 What will happen if V_d is decreased below the lower limit of this range?

(30) PROBLEM 4
Given is a full-bridge dc-dc converter (H-bridge) with dc motor load as shown (Fig. 30). The motor is modelled by the series connection of R_a, L_a and e_a. For control of the switches so called bipolar voltage switching is applied, where the control signals are obtained by comparing a control signal $v_{control}$ with a triangular waveform v_{tri}.

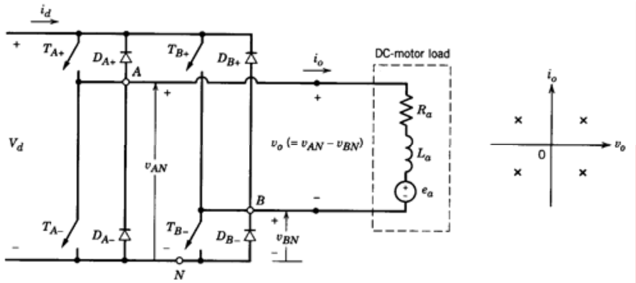


Fig. 30

The following is given:

T_s = 1 ms (T_s is the period of triangular waveform)
R_a = 0.1 Ohm
L_a = 2 mH
V_d = 300V
e_a = 120 V

For the calculation of the current waveform, the resistance R_a can be neglected.

(5) 4.1 Express the average value of v_o in V_d and $v_{control} / \hat{v}_{tri}$.
(5) 4.2 Calculate the required ratio of $v_{control} / \hat{v}_{tri}$ to maintain an average output current of I_0=+10A at e_a = +120 V.
(5) 4.3 Calculate the required ratio of $v_{control} / \hat{v}_{tri}$ to maintain an average output current of I_0= -10A at e_a = +120 V.
(15) 4.4 Sketch the $v_0(t)$, $i_0(t)$ and the source current i_d for I_0 = +10A at e_a = +120 V.

Summary of answers to exam *Electronic Power Conversion* dd 15 June 2005

1.1 See book of Mohan,

1.2 $E_{loss,sw}$ = 1/2 I_o V_d (t_{ri}+t_{fv}) + 1/2 I_o V_d(t_{rv}+t_{fi}) =
= 1/2 . I_o V_d (t_{ri}+t_{fv} + t_{rv}+t_{fi}) = 1/2 . 6 . 500 . (480ns) = 720 μJ
$P_{loss,sw}$ = f_s . $E_{loss,sw}$ = 720 f_s μW

1.3 $P_{loss,on}$ = V_{on} . I_{on} t_{on}/T_s = V_{on} . I_{on} D =1.5 . 6 . 0.6 = 5.4 W
$P_{loss,tot}$ = 5.4 + 720. 10^{-6} f_s W

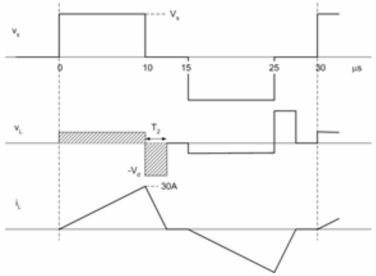
2.1 $P = \frac{1}{T}\int_0^T u\,i\,dt = \frac{2\cdot 230\sqrt{2}\cdot 10}{\pi}\cdot\cos 2\pi\delta = 2070\cos\pi\delta \quad W$

2.2 $I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2 dt} = 10\ A$

2.3 $PF = \frac{P}{U_{rms} I_{rms}} = \frac{2\sqrt{2}}{\pi}\cos 2\pi\delta = 0.9\cos 2\pi\delta$

2.4 $DPF = \frac{I_{1,rms}}{I_{rms}} = \frac{10\cdot 2\sqrt{2}/\pi}{10} = 0.9$ (Note that for a sinusoidal voltage: PF=DPF. cosφ)

3.1



3.2 $\hat{i}_s = \frac{1}{L}\int_0^{10\mu s} v_L\,dt = \frac{V_s - V_d}{L_m}T_{on} = \frac{(300-240)}{20\mu s}10\mu s = 30A$

T_2 follows from $v_{L,av} = 0 \rightarrow (V_s - V_d)10\mu s = V_d T_2 \rightarrow T_2 = \frac{V_s - V_d}{V_d}10\mu s = 2.5\mu s$

$I_{d,av} = \frac{1}{T_s/2}\int_0^{T_s/2} i_d\,dt = \frac{\hat{i}_s\cdot(10\mu s + T_2)}{2\cdot T_s/2} = \frac{30\cdot 12.5}{2\cdot 15} = 12.5A$

Because V_d is constant we can write: $P_d = V_d \cdot I_{d,av} = 240\cdot 12.5 = 3000W$

3.3 The time T_2 will increase when V_d decreases, because in steady state the average inductor voltage is zero: $v_{L,av} = 0 \rightarrow (V_s - V_d)\cdot T_{on} - V_d\cdot T_2 = 0$ or

$V_d = \frac{T_{on}}{T_2 + T_{on}}V_s$

The boundary for continuous conduction is reached when T_2=5ms

$V_d = \frac{T_{on}}{T_2 + T_{on}}V_s = \frac{10\mu s}{10\mu s + 5\mu s}300 = 200V$. Range: V_d>200V. Note : for V_d>300V there is no current flowing at all.

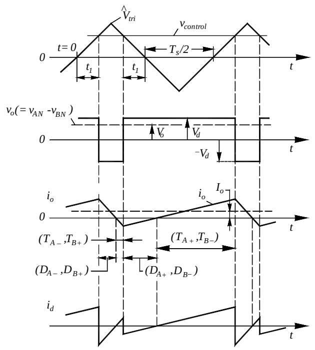
4.1 $V_0 = V_d\frac{v_{control}}{\hat{v}_{tri}}$

4.2 $v_o(t) + v_R(t) + v_L(t) - e_a(t) = 0$

After averaging: $V_0 + I_0 R - e_a = 0$

Or: $300\frac{v_{control}}{\hat{v}_{tri}} + 10\cdot R - 120 = 0$ so: $\frac{v_{control}}{\hat{v}_{tri}} = \frac{121}{300} = 0.403$; (D_1=0.702)

4.3 $\frac{v_{control}}{\hat{v}_{tri}} = \frac{119}{300} = 0.397$



I_0=10A

$$\Delta I_0 = \frac{(V_d - e_0)D_1 T_s}{L_a} = \frac{300-120}{2\cdot 10^{-3}} 0.702\cdot 10^{-3} = 63$$

positive peak current: 10 + 63/2 = 41.6 A
negative peak current: 10 - 63/2 = -21.6 A

4.4 Like Mohan fig. 7-29e

Exam *Electronic Power Conversion* 20 January 2006

(30) PROBLEM 1

For a forward converter a transformer is needed. For the transformer two pairs of so-called E-cores with identical shape are available (Fig. 31a), but they are made from different materials. The basic BH-loop of the respective materials are shown in Fig. 31b and c for the case of maximum excitation of the material. Only a part of the BH-loop will be used. Both the primary, the secondary and the auxiliary demagnetising winding of the forward converter are wound around the central leg. The turns ratio between primary and demagnetisation winding is 1.

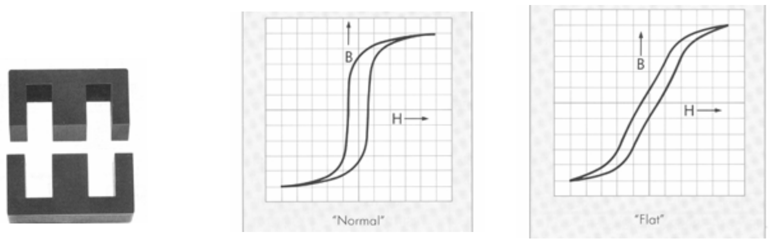


Fig. 31 a: double E-core; b: normal BH-loop; c: flat BH-loop.
For diagrams a and b: B-scale: 0.1 T per division; H-scale: 5 A/m per division

The E-cores have the following data:

A_c = 1 cm2 (Core cross section of central leg)
l_e = 4 cm (Equivalent length of magnetic path of field lines)

Other relevant material properties (B_s, B_r, H_c) can be read from the figure.
For the forward converter the following is given:

f_s = 75 kHz (switching frequency)
V_d = 300 V (supply voltage)

(10) 1.1 What type of material (normal loop or flat loop) is most suited for the application and why.
Sketch a typical loop that applies in normal operation of the forward converter.

(5) 1.2 Calculate the minimum number of turns $N_{1,min}$ for the selected type of material to avoid saturation. Read relevant data from Fig. 31. Sketch the flux density B as a function of time for D=0.5 and indicate minimum and maximum values.
(10) 1.3 Estimate the magnetizing inductance L_m for $N_1=N_{1,min}$ (20% accuracy is sufficient here).
(5) 1.4 Calculate the peak value of the current in the auxiliary winding.

(40) PROBLEM 2

Given is a forward converter as shown in Fig. 32

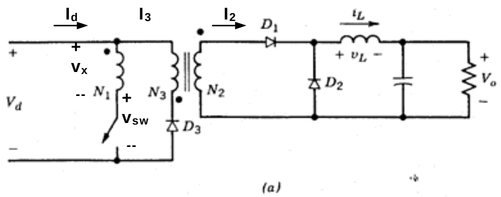


Fig. 32

Given is:

V_d = 300 V (nominal input voltage, however the actual voltage is variable)
V_0 = 6 V (nominal output voltage)
f_s = 100 kHz (switching frequency)
N_1:N_3 = 1 (turns ratio)
L_m = 15 mH (magnetising inductance of transformer, seen from primary side)
L_0 = 50 μH (output filter inductance)

The winding N_3 serves complete demagnetisation of the core.
(5) 2.1 When D = 0.4 and V_d=300V, calculate the turns ratio N_1:N_2 to get V_0=6V
(5) 2.2 Assume N_1:N_2 has the value that is calculated in 2.1. What is the lowest input voltage allowed if V_0 is to be kept equal to 6 V?

In the following, D = 0.4, V_d=300V, V_0=6V and I_0=10A.
(5) 2.3 Calculate the voltage over the transistor during the T_{off}.
(5) 2.4 Calculate the maximum values v_{sw}, i_L and the magnetising current of the transformer i_m.
(5) 2.5 Calculate I_0 for the boundary of discontinuous conduction mode.
(15) 2.6 Sketch v_d , v_{sw} , i_L, i_d, i_3 and i_m.

(30) PROBLEM 3

Given is a single-phase rectifier that is connected to a supply voltage v_s and a battery as shown in Fig. 33a. The battery is represented by a DC voltage V_d. The voltage v_s has a block-like shape as shown in Fig. 33b and that is produced by some HF inverter (not shown). The circuit is intended to charge the battery. Depending on the state-of-charge of the battery the voltage V_d may vary.

Given is:

$V_{d,nom}$=240V (nominal battery voltage)
V_s=300V (amplitude of v_s as shown in(Fig. 33b)
T_s=30μs (period of voltage v_s)
f_s= 1/T_s=33.3 kHz (frequency of v_s)
L_s=20 μH

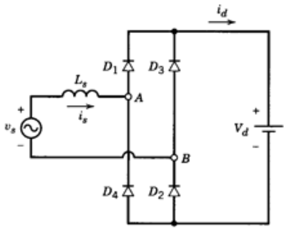


Fig. 33a

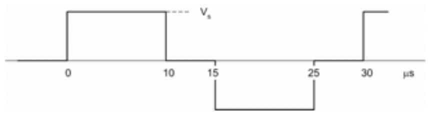


Fig. b

(10) 3.1 Sketch v_L and i_s as a function of time and indicate relevant values for $V_d = V_{d,nom}$.

(10) 3.2 Calculate the peak value of i_s, the average current I_d and the average output power P_d for $V_d = V_{d,nom}$.

(10) 3.3 What is the range of V_d for discontinuous conduction of i_d in a steady state.

Summary of answers to exam *Electronic Power Conversion* dd 20 January 2006

1.1 For a given core the ideal loop would be very steep with a large difference between B_s and B_r. On one hand a steep loop results in a small magnetising current resulting in less losses, although in general the losses caused by the magnetising current is small in comparison to the transformed load current ($N_1/N_2\ i_2$). On the other hand the number of turns depends on the available flux swing. For a forward converter the flux swing is B_s-B_r because of the unipolar excitation. The answer is that the flat core is preferred because of the much larger flux swing, resulting is less turns and less losses. Select B_{max}=+0.4 to have some margin to saturation. B_r=+0.1

1.2 $\Delta B\, N_1\, A_c = \int_0^{DT_s} v_1 dt$ or $N_1 = \dfrac{DV_d}{f_s A_c (B_s - B_r)} = \dfrac{0.5\cdot 300}{75\cdot 10^3\cdot 10^{-4}(0.4-0.1)} = 67$

1.3 $L_m = \dfrac{\mu N^2 A_c}{l_e}$ (this follows from eq. 3-60 and 3-80) where μ ($=\mu_0\mu_r$) is obtained from the BH-loop:

$\mu = B/H \approx 0.5/20 = 0.025$; $L_m = \dfrac{0.025\cdot 67^2\cdot 10^{-4}}{0.04} = 280\,mH$

1.4 Because N_1=N_3, the peak value of the current in the auxiliary winding is equal to the peak value of the magnetising current.

$\hat{i}_m = \dfrac{1}{L_c}\int_0^{DT_s} V_d dt = \dfrac{300\cdot 0.5}{75\cdot 10^3\cdot 280\cdot 10^{-3}} = 7.1\,mA$

Another way:

$\hat{H}\, l = N\, \hat{i}_m$ or $\hat{i}_m = \dfrac{\hat{H}\, l}{N} = \dfrac{12.5\cdot 0.04}{67} = 7.4mA$

2.1 $V_0 = D\dfrac{N_2}{N_1}V_d \rightarrow \dfrac{N_1}{N_2} = \dfrac{DV_d}{V_0} = \dfrac{0.4\cdot 300}{6} = 20$

2.2 $V_{d,\min} = \dfrac{V_0}{D_{\max}}\dfrac{N_1}{N_2} = \dfrac{6\cdot 20}{0.5} = 240V$. (Note:$N_1$:$N_3$=1 ➔ D_{max}=0.5)

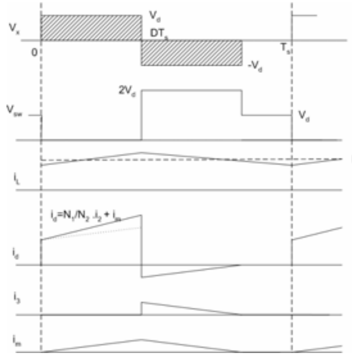
2.3 $v_{sw} = V_d + \dfrac{N_1}{N_3}V_d = 300 + 300 = 600V$

2.4 $V_{T,max}$=600V; $\hat{i}_m = \dfrac{DT_sV_d}{L_m} = \dfrac{0.4\cdot 10\cdot 10^{-6}\cdot 300}{15\cdot 10^{-3}} = 80mA$

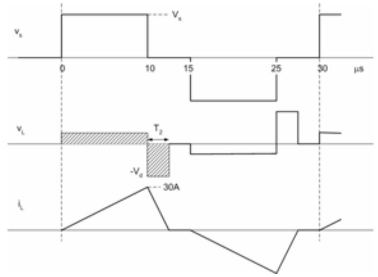
$\hat{i}_m = I_0 + \dfrac{(1-D)T_sV_0}{2L_0} = 10 + \dfrac{0.6\cdot 10\cdot 10^{-6}\cdot 6}{2\cdot 50\cdot 10^{-6}} = 10 + \dfrac{0.72}{2} = 10.36A$

2.5 $\Delta I_{L,pp} = \dfrac{(1-D)T_sV_0}{L_0} = 0.72A$. Load current on the boundary: $I_{0,B} = \dfrac{\Delta I_L}{2} = 0.36A$

2.6



3.1



3.2 $\hat{i}_s = \dfrac{1}{L}\int_0^{10\mu s} v_L\, dt = \dfrac{V_s - V_d}{L_m}\, T_{on} = \dfrac{(300-240)}{20\mu H}10\mu s = 30A$

T_2 follows from $v_{L,av} = 0 \rightarrow (V_s - V_d)10\mu s = V_d T_2 \rightarrow T_2 = \dfrac{V_s - V_d}{V_d}10\mu s = 2.5\mu s$

$I_{d,av} = \dfrac{1}{T_s/2}\int_0^{T_s/2} i_d\, dt = \dfrac{\hat{i}_s\cdot(10\mu s + T_2)}{2\cdot T_s/2} = \dfrac{30\cdot 12.5}{2\cdot 15} = 12.5A$

Because V_d is constant we can write: $P_d = V_d\cdot I_{d,av} = 240\cdot 12.5 = 3000W$

3.3 The time T_2 will incease when V_d decreases, because in steady state the average inductor voltage is zero: $v_{L,av} = 0 \rightarrow (V_s - V_d)\cdot T_{on} - V_d\cdot T_2 = 0$ or

$V_d = \dfrac{T_{on}}{T_2 + T_{on}}V_s$

The boundary for continuous conduction is reached when T_2=5ms

$V_d = \dfrac{T_s/2}{T_s/2 + T_{on}}V_s = \dfrac{10\mu s}{10\mu s + 5\mu s}300 = 200V$. Range for discontinuous conduction:

V_d>200V. Note: for V_d>300V there is no current flowing at all.

3.4 When V_d<200V the current is continuous. At instants k.T_s/2 the current will not be reduced to zero yet. Just after these instants the current is opposed by the voltage $|V_d+V_s|$ until the current has a zero crossing, after which it is opposed by $|V_s$-$V_d|$.

Exam 'Electronic Power Conversion' 21 June 2006

(20) PROBLEM 1

Consider the resistive switching circuit shown in Fig. 35 with V_d=300 V, f_s=100kHz and R=75 Ohm. The switch turn-on time is t_{on} =150 ns and the switch turn-off time is t_{off}=300 ns. Assume linear voltage and current switching characteristics.

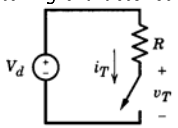


Fig. 34

(5) 1.1 Sketch the waveforms of v_T and i_T and the power p_T that is dissipated in the switch as a function of time.
(10) 1.2 Calculate and plot the average switching power loss as a function of frequency in the frequency range 25 kHz-100 kHz.
(5) 1.3 Calculate the efficiency η of the power transfer from the source V_d to the load R at 100 kHz and a duty ratio D=0.5.

(40) PROBLEM 2

Given is a forward converter as shown in Fig. 35

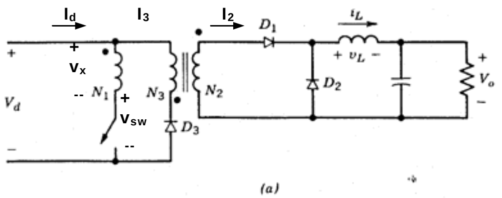


Fig. 35

Given is:

V_d = 300 V	(nominal input voltage, however the actual voltage is variable)
V_0 = 6 V	(nominal output voltage)
f_s = 100 kHz	(switching frequency)
N_1:N_3 = 1	(turns ratio)
L_m = 15 mH	(magnetising inductance of transformer, seen from primary side)
L = 50 μH	(output filter inductance)

The winding N_3 serves complete demagnetisation of the core.

(5) 2.1 When D = 0.4 and V_d=300V, calculate the turns ratio N_1:N_2 to get V_0=6V
(5) 2.2 Assume N_1:N_2 has the value that is calculated in 2.1. What is the lowest input voltage allowed if V_0 is to be kept equal to 6 V?

In the following, D = 0.4, V_d=300V, V_0=6V and I_0=10A.

(5) 2.3 Calculate the voltage over the transistor during the T_{off}.
(5) 2.4 Calculate the maximum values v_{sw}, i_L and i_m.
(5) 2.5 Calculate I_0 for the boundary of discontinuous conduction mode.
(15) 2.6 Sketch v_x , v_{sw} , i_L, i_1, i_3 and i_m.

(40) PROBLEM 3

For a certain application a dc voltage has to be stepped up from a source voltage V_s to a higher load voltage V_0. The voltage across the load should be fairly constant. The half-bridge circuit as shown in Fig. 36 is available, however the circuit is not complete yet and at least an inductor L has to be added. On the other hand some other components in the circuit are superfluous . The indicated terminals are not necessarily the terminals that have to be used as input and output.

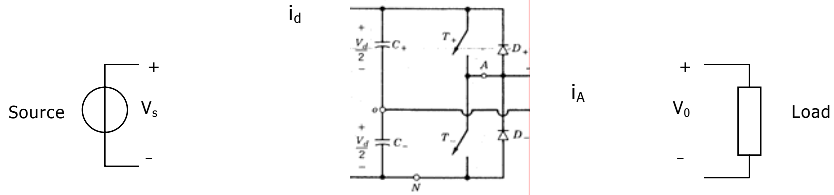


Fig. 36

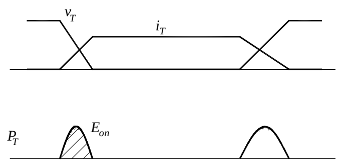
The following is specified:
V_s=150V, V_0=240V, f_s=20 kHz and C_+=C_-= 4700μF and P_0=500W.
Inductor L=600μH.

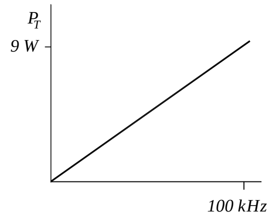
(5) 3.1 What type of converter would you preferably use for this conversion?
(10) 3.2 Show by means of a circuit diagram how the desired conversion can be obtained by using the circuit from Fig. 36. Show where the inductor L should be added and include the connections to source and load. Describe shortly how the circuit is operated.
(5) 3.3 Express V_o in the duty ratio D and V_s . Define and calculate the duty ratio D.
(10) 3.4 Calculate the average inductor current. Sketch for L=600μH the terminal current i_A , the diode current i_{D+} and the voltage v_{AN} or v_{A0} .
(10) 3.5 Can i_A have zero crossings? Calculate the minimum value of the inductor that guarantees that, for the given conditions, the inductor current is always positive.

Summary of answers to exam *Electronic Power Conversion* dd 21 June 2006

1.4 Note that the waveforms for the switching of resistive loads are quite different from the waveforms for clamped inductive loads (Mohan Fig 2-6). With the circuit from the exam v_T and i_T are always related by: $v_T = V_d - i_T R$ v_T

During turn on: i_T=I_d t/t_{on} and v_T=V_d(1-t/t_{on}) ; p_T(t)=v_T i_T = V_d I_d t/t_{on} (1-t/t_{on}).
Similar during turn off.





1.5 Dissipated energy during turn on: $E_{T,on} = \int_0^{ton} i_T v_T dt = V_d I_d \left(\frac{1}{2}\frac{t^2}{t_{on}} - \frac{1}{3}\frac{t^3}{t_{on}^2} \right)\Bigg|_0^{ton} = \frac{V_d I_d}{6} t_{on}$ =300*4*1/6*150 ns (J)

Similar for turn off.

Average power: $P_T = \frac{V_d I_d}{6} \frac{(t_{on} + t_{off})}{T_s}$ =200 . (150+300) . 10^{-9} . f_s.

$$\eta = \frac{P_R}{P_d} = \frac{P_d - P_T}{P_d} = \frac{DV_d I_d - P_T}{DV_d I_d} = \frac{600-9}{600} = 0.985$$

2.1 $V_0 = D\frac{N_2}{N_1}V_d \quad \rightarrow \quad \frac{N_1}{N_2} = \frac{DV_d}{V_0} = \frac{0.4 \cdot 300}{6} = 20$

2.2 $V_{d,\min} = \frac{V_0}{D_{\max}}\frac{N_1}{N_2} = \frac{6 \cdot 20}{0.5} = 240V$. (Note:$N_1$:$N_3$=1 ➔ D_{max}=0.5)

2.3 $v_{sw} = V_d + \frac{N_1}{N_3}V_d = 300 + 300 = 600V$

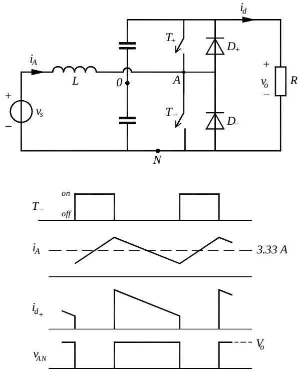
2.4 $V_{T,max}$=600V; $\hat{i}_m = \frac{DT_s V_d}{L_m} = \frac{0.4 \cdot 10 \cdot 10^{-6} \cdot 300}{15 \cdot 10^{-3}} = 80mA$

$$\hat{i}_m = I_0 + \frac{(1-D)T_s V_0}{2L_0} = 10 + \frac{0.6 \cdot 10 \cdot 10^{-6} \cdot 6}{2 \cdot 50 \cdot 10^{-6}} = 10 + \frac{0.72}{2} = 10.36A$$

2.5 $\Delta I_{L,pp} = \frac{(1-D)T_s V_0}{L_0} = 0.72A$. Load current on the boundary: $I_{0,B} = \frac{\Delta I_L}{2} = 0.36A$

3.1 Boost converter (Mohan section 7-4 and Fig 7-33).

3.2 The circuit should be configured such that a boost converter is obtained (Mohan section 7-4 and Fig 7-33). T_ and D+ are the active components. Note that the terminal pair {A ,O} cannot be used as input as the node 0 cannot absorb a DC current. The capacitors C+ , C- are in parallel to the load as is required in a boost converter. When T_ is ON the current through L increases and when T_ is OFF the inductor current is 'pushed' in the output circuit via D+.



3.3 $V_0 = \frac{1}{1-D}V_s$ with D=T_{on}/T_s where T_{on} is the on-time of T_ and T_s=1/f_s ; D=0.375

3.4 I_A=500/150=3.33A ; I_d=500/240=2.08A ; R=500/2.08=115 Ohm ; peak-to-peak value of the current: $\Delta i_{A,pp} = \frac{DT_S}{L}V_s\sqrt{a^2+b^2}$ = 4.72 A

3.5 I_A can have zero crossings if L is small. In that case T+ conducts during the negative part of I_A. The condition for not having zero crossing is similar to the condition for continuous conduction mode with up-converters (see Mohan eq. 7-28). $L_{\min} = \frac{DT_S}{\hat{I}_A}V_s = \frac{DT_S}{2I_A}V_s = \frac{0.375 \cdot 50 \cdot 10^{-6}}{2 \cdot 3.33}150 =$ 422μH

Note that RC>>T_s, so that V_d is indeed constant during a switching period.

Combined exam ET3165-D1 and ET4119 ; 19 January 2007

(20) PROBLEM 1

Given is a simple circuit with a generic switch as shown in Fig. 37.

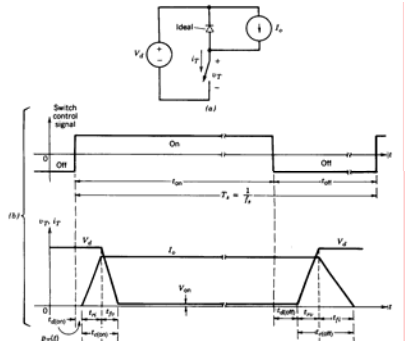


Fig. 37

The data sheet of the switch specifies the following switching times corresponding to the linear switching characteristics as shown in the figure.

t_{ri} = 80 ns ;
t_{fv} = 80 ns ;
t_{rv} = 120 ns ;
t_{fi} = 200 ns

Further: V_d=500V ;
I_0 = 6A.

(5) 1.1 Sketch the instantaneous switching loss as a function of time.

(10) 1.2 Calculate the switching power loss as a function of the switching frequency in a range 25 - 100 kHz, assuming V_d=500V and I_0 = 6A.

(5) 1.3 Calculate and plot the total losses as a function of the switching frequency in a range 25 - 100 kHz in the switch when the on-state voltage is V_{on} =1.5V at 6A and the duty ratio of the switch is D = 0.6 (assume $t_{d(on)}$=$t_{d(off)}$).

(40) PROBLEM 2

Given is a single-phase rectifier that is connected to a supply voltage vs and a battery as shown in Fig. 38a. The battery is represented by a DC load voltage Vd. The voltage vs has a block-like shape (Fig. 38b) that is produced by some HF inverter (not shown). The rectifier is intended to charge the battery. Depending on the charging state of the battery the voltage V_d may vary.

Given is: $V_{d,nom}$=240V (nominal voltage of V_d)
V_s=300V (amplitude of vs as shown in Fig. 38b)
T_s=30μs (period of voltage vs)
f_s= 1/T_s=33.3 kHz (frequency of vs)
L_s=20 μH

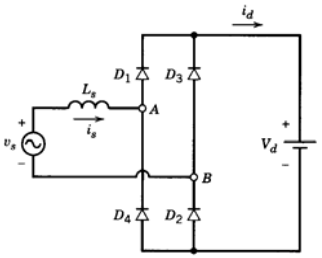


Fig. 38a

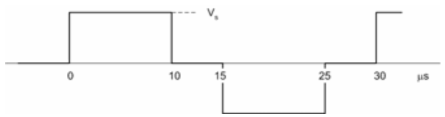


Fig. b

(10) 2.1 Sketch v_L and i_s as a function of time and indicate relevant values for $V_d = V_{d,nom}$.
(10) 2.2 Calculate the peak value of i_s, the average current I_d and the average output power P_d for $V_d = V_{d,nom}$.
(10) 2.3 What is the range of V_d for discontinuous conduction of i_d in a steady state.
(10) 2.4 What will happen if V_d is decreased below the lower limit of this range?

(40) PROBLEM 3

Given is a full-bridge dc-dc converter (H-bridge) with dc motor load as shown (Fig. 39). The motor is modelled by the series connection of R_a, L_a and e_a. For control of the switches so called bipolar voltage switching is applied, where the control signals are obtained by comparing a control signal $v_{control}$ with a triangular waveform v_{tri}.

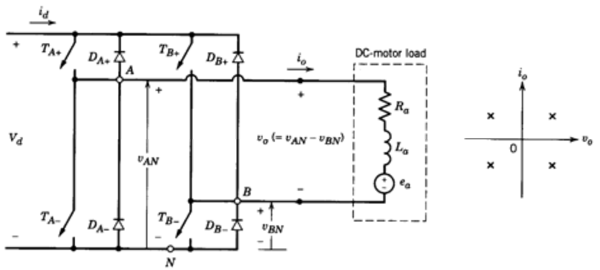


Fig. 39

The following is given:

- T_s = 1 ms (T_s is the period of triangular waveform)
- R_a = 0.1 Ohm
- L_a = 2 mH
- V_d = 300V
- e_a = 120 V

For the calculation of the current waveform, the resistance R_a can be neglected.
(10) 3.1 Express the average value of v_o in V_d and $v_{control} / \hat{v}_{tri}$.
(10) 3.2 Calculate the required ratio of $v_{control} / \hat{v}_{tri}$ to maintain an average output current of I_0=+10A at e_a = +120 V.
(5) 3.3 Calculate the required ratio of $v_{control} / \hat{v}_{tri}$ to maintain an average output current of I_0= -10A at e_a = +120 V.
(15) 3.4 Sketch the $v_0(t)$, $i_0(t)$ and the supply current $i_d(t)$ for I_0 = +10A at e_a = +120 V.

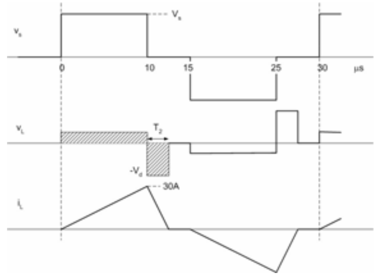
Summary of answers to exam ET3165-D1 and ET4119 dd 17 Jan 2007

1.1 See book of Mohan,

1.2 $E_{loss,sw} = 1/2\ I_o V_d (t_{ri}+t_{fv}) + 1/2\ I_o V_d (t_{rv}+t_{fi}) =$
$= 1/2 \cdot I_o V_d (t_{ri}+t_{fv}+t_{rv}+t_{fi}) = 1/2 \cdot 6 \cdot 500 \cdot (480ns) = 720\ \mu J$
$P_{loss,sw} = f_s \cdot E_{loss,sw} = 720\ f_s\ \mu W$

1.3 $P_{loss,on} = V_{on} \cdot I_{on}\ t_{on}/T_s = V_{on} \cdot I_{on}\ D = 1.5 \cdot 6 \cdot 0.6 = 5.4$ W
$P_{loss,tot} = 5.4 + 720 \cdot 10^{-6} f_s$ W

2.1



2.2 $$\hat{i}_s = \frac{1}{L}\int_0^{10\mu s} v_L\, dt = \frac{V_s - V_d}{L_m} T_{on} = \frac{(300-240)}{20\mu H} 10\mu s = 30A$$

T_2 follows from $v_{L,av} = 0 \rightarrow (V_s - V_d)10\mu s = V_d T_2 \rightarrow T_2 = \frac{V_s - V_d}{V_d} 10\mu s = 2.5\mu s$

$$I_{d,av} = \frac{1}{T_s/2}\int_0^{T_s/2} i_d\, dt = \frac{\hat{i}_s \cdot (10\mu s + T_2)}{2 \cdot T_s/2} = \frac{30 \cdot 12.5}{2 \cdot 15} = 12.5A$$

Because V_d is constant we can write: $P_d = V_d \cdot I_{d,av} = 240 \cdot 12.5 = 3000W$

2.3 The time T_2 will incease when V_d decreases, because in steady state the average inductor voltage is zero: $v_{L,av} = 0 \rightarrow (V_s - V_d) \cdot T_{on} - V_d \cdot T_2 = 0$ or

$$V_d = \frac{T_{on}}{T_2 + T_{on}} V_s$$

The boundary for continuous conduction is reached when T_2=5ms

$$V_d = \frac{T_s/2}{T_s/2 + T_{on}} V_s = \frac{10\mu s}{10\mu s + 5\mu s} 300 = 200V.$$ Range for discontinuous conduction:

V_d>200V. Note: for V_d>300V there is no current flowing at all.

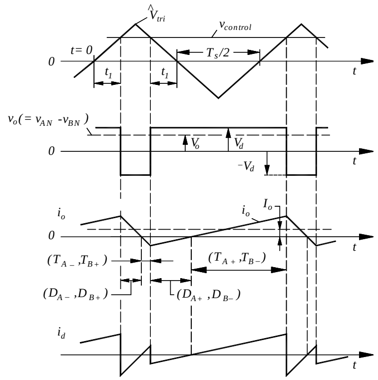
2.4 When V_d<200V the current is continuous. At instants $k.T_s/2$ the current will not be reduced to zero yet. Just after these instants the current is opposed by the voltage $|V_d+V_s|$ until the current has a zero crossing, after which it is opposed by $|V_s-V_d|$.

3.1 $$V_0 = V_d \frac{v_{control}}{\hat{v}_{tri}}$$

3.2 $v_o(t) + v_R(t) + v_L(t) - e_a(t) = 0$
After averaging: $V_0 + I_0 R - e_a = 0$

Or: $300\frac{v_{control}}{\hat{v}_{tri}} + 10\cdot R - 120 = 0$ so: $\frac{v_{control}}{\hat{v}_{tri}} = \frac{121}{300} = 0.403$; (D_1=0.702)

3.3 $\frac{v_{control}}{\hat{v}_{tri}} = \frac{119}{300} = 0.397$



I_0=10A

$$\Delta I_0 = \frac{(V_d - e_0)D_1 T_s}{L_a} = \frac{300-120}{2\cdot 10^{-3}}0.702\cdot 10^{-3} = 63$$

positive peak current: 10 + 63/2 = 41.6 A
negative peak current: 10 - 63/2 = -21.6 A

3.4 Like Mohan fig. 7-29e

Exam ET4119 and ET3165-D1 on 20 June 2007

(20) PROBLEM 1

Consider the resistive switching circuit shown in Fig. 11 with V_d=300 V, f_s=100kHz and R=75 Ohm. The switch turn-on time is t_{on} =150 ns and the switch turn-off time is t_{off}=300 ns. Assume linear voltage and current switching characteristics.

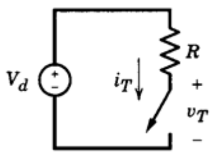


Fig. 40

(10) 1.1 Sketch the waveforms of v_T and i_T and the power p_T that is dissipated in the switch as a function of time.
(5) 1.2 Calculate and plot the average switching power loss as a function of frequency in the frequency range 25 kHz-100 kHz.
(5) 1.3 Calculate the efficiency η of the power transfer from the source V_d to the load R at 100 kHz and a duty ratio D=0.5.

(40) PROBLEM 2

Given is a forward converter as shown in Fig. 32

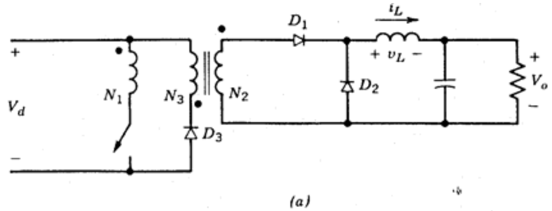


Fig. 41

Given is:

V_d = 200…350 V	(input voltage range)
V_0 = 5 V	(nominal output voltage)
f_s = 125 kHz	(switching frequency)
N_1:N_3 = 2:1	(turns ratio)
L_m = 15 mH	(magnetising inductance of transformer, seen from primary side)
L = 10 μH	(output filter inductance)
P_0= 20...300 W	(output power range @5V)

Both the supply voltage and the load power P_0 may vary between the indicated values.
The winding N_3 serves complete demagnetisation of the core. Note the unusual winding ratio N_1:N_3.

(5) 2.1 Calculate the turns ratio N_1:N_2 to get V_0=5V at a nominal input voltage V_d=325V and D=0.4
(5) 2.2 D should be varied to maintain a constant output voltage at variable input voltage. What is the maximum allowable value of D to guarantee complete demagnetisation of the transformer?
(10) 2.3 What is the lowest allowable input voltage V_d to avoid transformer saturation? Check whether the control range of D corresponds to the input voltage range.

In the following, D = 0.4, V_d=325V, V_0=5V and I_0=50A.

(5) 2.4 Calculate the maximum values v_{sw}, i_L and i_m.
(5) 2.5 Calculate I_0 for the boundary of discontinuous conduction mode. Check this results with the given minimum load current.
(10) 2.6 Sketch v_1 , v_{sw} , i_L, i_1, i_3 and i_m.

(40) PROBLEM 3

In Fig. 10a a single-line diagram a power system with power electronic load is shown. The utility power source (dashed block) is represented by a sinusoidal voltage sources v_s in series with an inductance L_s in each phase. The nominal rms value of the phase-to-neutral voltage is V_s=230V and its fundamental frequency is f_s=60 Hz.
The power electronic load is a large industrial three-phase diode rectifier as shown in Fig. 10b. The load of the rectifier is represented by a constant DC current source I_d.

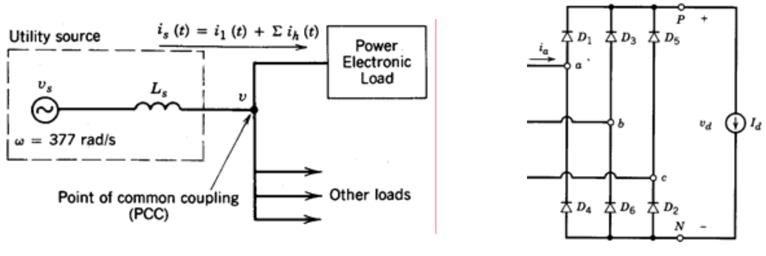


Fig. 42

(10) 3.1 Calculate the average rectifier output voltage V_d as a function of V_s, L_s and I_d.
(10) 3.2 Sketch i_a and v_d and calculate the harmonics of the input current i_a as a function of I_d for L_s=0.
(10) 3.3 Describe qualitatively the effect of $L_s \neq 0$ instead of L_s=0 on the input current harmonics. Consider both high-order harmonics and low-order harmonics. Give a qualitative sketch of i_a and v_d

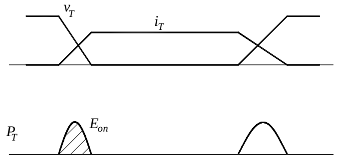
According to local regulations of the utility company, the maximum allowable fifth harmonic voltage at PCC caused by any load should be less than 3% of the nominal voltage.

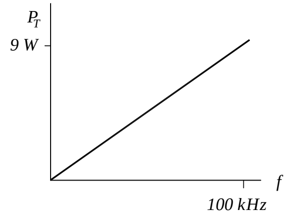
(10) 3.4 Calculate the maximum allowable value of I_d when L_s=3 mH. You may assume for this case that the rms value of the fifth harmonic of the rectifier current is equal to I_{a5} = 0.15 I_d

Summary of answers to exam *Electronic Power Conversion* dd 20 June 2007

1.1 Note that the waveforms for the switching of resistive loads are quite different from the waveforms for clamped inductive loads (Mohan Fig 2-6). With the circuit from the exam v_T and i_T are always related by: $v_T = V_d - i_T R$. During turn on: $i_T = I_d\, t/t_{on}$ and $v_T = V_d(1-t/t_{on})$;

Power as a function of time: $p_T(t) = v_T i_T = \frac{t}{t_{on}} V_d \cdot (1 - \frac{t}{t_{on}}) I_d$; Similar during turn off.





1.2 Dissipated energy during turn on: $E_{T,on} = \int_0^{ton} i_T v_T dt = V_d I_d \left(\frac{1}{2}\frac{t^2}{t_{on}} - \frac{1}{3}\frac{t^3}{t_{on}^2} \right)\Bigg|_0^{ton} = \frac{V_d I_d}{6} t_{on}$ = 300 . 4 . 1/6 . 150 .10^{-9} = 30 μJ

Similar for turn off.

Average power: $P_T = \frac{V_d I_d}{6}(t_{on} + t_{off})/T_s$ = 200 * (150+300) * 10^{-9} * f_s = 90.10^{-6} f_s (W)

$$\eta = \frac{P_R}{P_d} = \frac{P_d - P_T}{P_d} = \frac{DV_d I_d - P_T}{DV_d I_d} = \frac{600-9}{600} = 0.985$$

2.1 $V_0 = D\frac{N_2}{N_1}V_d \quad \rightarrow \quad \frac{N_1}{N_2} = \frac{DV_d}{V_0} = \frac{0.4 \cdot 325}{5} = 26$

2.2 For steady state operation the transformer should completely be demagnetised in each cycle or the average voltage across each winding should be zero. For w_3 this means:

$$D_{\max} V_d \frac{N_3}{N_1} = (1 - D_{\max})V_d \quad \rightarrow \quad D_{\max} = 0.667$$

2.3 The highest value of D is needed at the lowest input voltage.

$V_0 = D\frac{N_2}{N_1}V_d \quad \rightarrow \quad V_{d,\min} = \frac{N_1 V_0}{N_2\, D_{\max}} = \frac{26 \cdot 5}{0.667} = 195V$. Because the lowest specified input voltage is 200V, the range of D is large enough to handle the input voltage range.

2.3 $v_{sw} = V_d + \frac{N_1}{N_3}V_d = 325 + 2 \cdot 325 = 975V$!

$$\hat{i}_m = \frac{DT_s V_d}{L_m} = \frac{0.4 \cdot 8 \cdot 10^{-6} \cdot 325}{15 \cdot 10^{-3}} = 69.3mA$$

$$\hat{i}_L = I_0 + \frac{(1-D)T_s V_0}{2L_0} = 50 + \frac{0.6 \cdot 8 \cdot 10^{-6} \cdot 5}{2 \cdot 10 \cdot 10^{-6}} = 50 + \frac{2.4}{2} = 51.2A$$

2.5 $\Delta I_{L,pp} = \frac{(1-D)T_s V_0}{L_0} = 2.4A$. Load current on the boundary: $I_{0,B} = \frac{\Delta I_L}{2} = 1.2A$

Because the minimum load current (2A) is smaller then $I_{0,B}$, the converter operates in continues conduction mode.

2.6 Sketch: see Mohan fig. 10-11

3.1 See text book eq. 5-68 and 5-86. $V_d = \frac{3\sqrt{2}}{\pi}V_{LL} - \frac{3}{\pi}\omega L_s I_d = 1.35V_{LL} - \frac{3}{\pi}\omega L_s I_d$, where the phase voltage V_S is given by $V_{LL} = \sqrt{3}\, V_S$; $V_d = \frac{3\sqrt{6}}{\pi}V_s - \frac{3}{\pi}\omega L_s I_d = 535 - 1.8 I_d$

3.2 See text book fig. 5-32 partly.

Rms of fundamental: $I_{a1} = \sqrt{\frac{2}{3}} I_d$; Harmonics: $I_{ah} = \frac{I_{a1}}{h} \quad for\ h = 5, 7, 11, 13, ...$
$= 0 \quad else$

3.3 All harmonics are more or less reduced, including the fundamental. Higher harmonics are attenuated more than the lower harmonics, because the impedance of L_s increases with frequency. Lower harmonics are only slightly affected.

3.4 Requirement from utility: $V_{s5} < 0.03 V_s$ (textbook, eq 18-2)

with $V_{s5} = 5\omega L_s I_{a5} = 5\omega L_s \cdot 0.15 I_d \quad \rightarrow 5\omega L_s \cdot 0.15 I_d < 0.03\ V_s$ or $I_d < 8.13A$