Examination **ENM060 Power Electronic Converters**

Date and time Tuesday April 14th, 2015, 14:00 – 18:00

Responsible Teacher: Andreas Karvonen, tel. 0709-524924

Authorised Aids: Chalmers-approved calculator (Casio FX82..., Texas Instruments Ti30... and Sharp ELW531...)

Grades: U, 3, 4 or 5. (The limit for a 3 on the exam is 20p, a 4 is 30p and 5 is 40p. The maximum number of points is 50.)

Solutions: Course webpage (Ping-Pong), April 15th 2015

Review of Exam May 11th and May 13th, 12:00-13:00.
Fredrik Lamms Room. Division of Electric Power Engineering (1st floor).

From May 15th 2015, the exams can be picked-up at the exam office, Department of Energy and Environment.
Location: EDIT building, Maskingränd 2, 3Ö (east) floor, room 3434A.
Opening hours during semesters: Monday-Friday 12:30-14:30

Observe that the questions are not arranged in any kind of order.

On the last pages there are some formulas that can be used in the examination. Always assume steady-state conditions in all tasks unless otherwise stated.

Please, read through the exam before you start.

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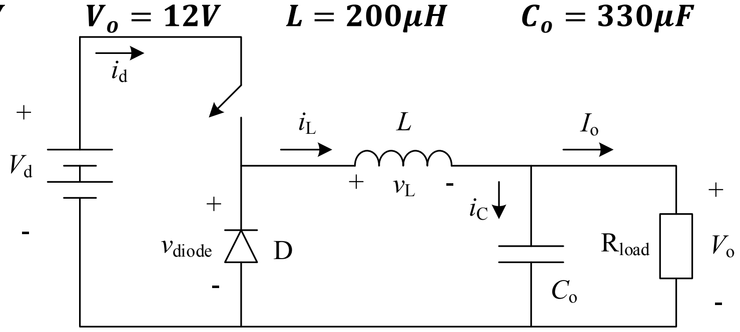
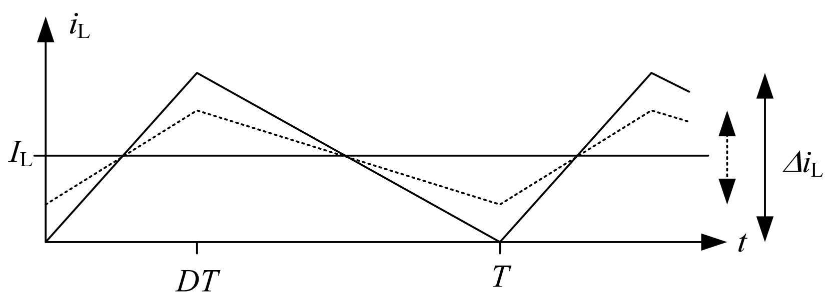
1) Consider the buck converter below. Calculate the maximum switching frequency that can be used if the converter always shall operate in CCM. (4p)

$30V \leq V_d \leq 40V$ $V_o = 12V$ $L = 200\mu H$ $C_o = 330\mu F$ $0.5A \leq I_o \leq 7A$



The converter is operating in CCM if $I_L \geq \Delta i_L/2$, see figure:



If the average value of the inductor current is equal to half the peak-to-peak ripple in the inductor current, the converter will be operating at the border between DCM and CCM, see the solid line in the figure. If the ripple is reduced there will be a margin to the border, see the dashed line. First we find an expression for the duty ratio. This can be done by calculating the average inductor voltage.

$$V_L = \frac{1}{T_{sw}}\left(\int_0^{DT_{sw}} (V_{in} - V_{out})dt + \int_{DT_{sw}}^{T_{sw}} (-V_{out})dt\right) = \frac{1}{T_{sw}}(V_{in}DT_{sw} - V_{out}DT_{sw} - V_{out}T_{sw} + V_{out}DT_{sw}) = 0$$

$$V_{out} = V_{in}D \quad \rightarrow \quad D_1 = \frac{V_{out}}{V_{in}} = \frac{12V}{30V} = 0.4 \qquad D_2 = \frac{V_{out}}{V_{in}} = \frac{12V}{40V} = 0.3$$

The average output current equals the average inductor current.

$$I_{out} = I_L \qquad 0.5A \leq I_{out} \leq 7A$$

The peak-to-peak ripple in the inductor current can be calculated. During the period $0 \leq t \leq DT_{sw}$ is the inductor voltage constant and equal to the input voltage. The equation can then be written as:

$$v_L = L\frac{di_L}{dt} = L\frac{\Delta i_L}{\Delta t} \qquad \rightarrow \qquad \Delta i_L = \frac{(V_{in} - V_{out})DT_{sw}}{L}$$

For CCM:

$$\frac{\Delta i_L}{2} < I_L$$

If we use the expressions above and rearrange a bit, the following holds for the switching frequency in CCM:

$$f_{sw} > \frac{(V_{in} - V_{out})D}{2I_L L} \qquad \Rightarrow \qquad f_{sw} > \frac{V_{out}(1-D)}{2I_o L}$$

The switching frequency, f_{sw}, shall always be greater than the right hand expression, therefore:

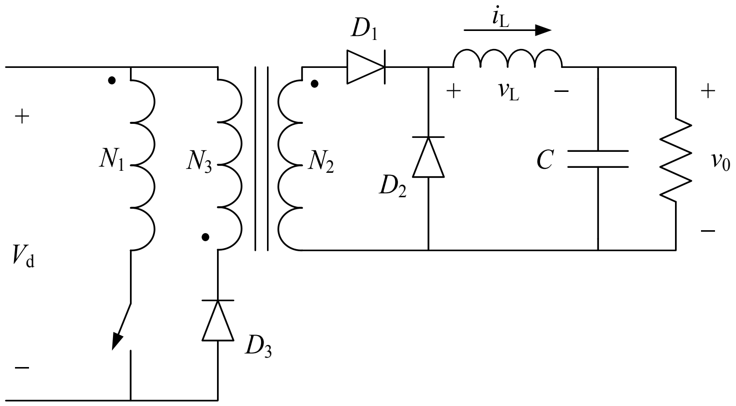
$$f_{sw-min} = max\left(\frac{V_{out}(1-D)}{2I_o L}\right) = max\left(\frac{12V(1-0.3)}{2 \cdot 0.5A \cdot 200\mu H}\right) = 42\ kHz$$

which is given for the lowest output current, $I_o = 0.5A$, and the lowest duty cycle, D=0.3, which in turn corresponds to the highest input voltage, $V_{in} = 40V$.

2) A transformer is added to the buck converter in (1) so that it becomes a Forward converter. Name two reasons for having a galvanically isolated output from your DC/DC converter. (2p)

- To avoid circulating currents
- Safety reasons
- Multiple outputs

3) The forward converter below is operated with a varying output voltage. Select suitable values for the output inductance (L_{out}) and the output capacitance (C_{out}) so that converter meets the specifications of current (Δi_L) and voltage (Δv_o) ripple. Assume that $N_1 = N_3$, $N_2/N_1 = 0.36$ and that the converter shall always operate in CCM. (5p)



$$\mathbf{360V \le V_d \le 400V \qquad V_o = 54V \qquad f_{sw} = 100kHz \qquad P_o = 500W}$$
$\Delta i_{L(peak-peak)} \le 20\%$ of the load current
$\Delta v_{o(peak-peak)} \le 20mV$

Since the number of turns on the primary winding is equal to the number of turns on the demagnetizing winding, the maximum allowed duty-cycle is 50%. If it becomes greater, the core will not have time to demagnetize.

$$I_O = \frac{P_O}{V_O} = \frac{500W}{54V} = 9.3A$$
$$i_{L(peak-peak)} = 0.2 \cdot I_O = 1.86A$$

$$D_{max} = \frac{V_{out}}{V_{in}}\frac{N_1}{N_2} = \frac{54V}{360V}\frac{1}{0.36} = 0.417$$

$$D_{min} = \frac{V_{out}}{V_{in}}\frac{N_1}{N_2} = \frac{54V}{400V}\frac{1}{0.36} = 0.375$$

$$V_{\sec(Dmax)} = \frac{N_2}{N_1}V_{in} = 0.36 \cdot 360V = 130V$$
$$V_{sec(Dmin)} = \frac{N_2}{N_1}V_{in} = 0.36 \cdot 400V = 144V$$

The output inductor is dimensioned for the highest duty cycle, a decrease in duty cycle will keep the converter in CCM.

$$\Delta i_{L(Dmax)} = \frac{v_L \Delta t}{L} = \frac{(V_{sec} - V_o) \cdot DT_{sw}}{L} \le 1.86A \quad \rightarrow \quad L \ge \frac{(V_{sec} - V_o) \cdot DT_{sw}}{\Delta i_L} = \frac{(130V - 54V) \cdot 0.417}{1.86A \cdot 100kHz} = 170\mu H$$
$$\Delta i_{L(Dmin)} = \frac{v_L \Delta t}{L} = \frac{(V_{sec} - V_o) \cdot DT_{sw}}{L} \le 1.86A \quad \rightarrow \quad L \ge \frac{(V_{sec} - V_o) \cdot DT_{sw}}{\Delta i_L} = \frac{(144V - 54V) \cdot 0.375}{1.86A \cdot 100kHz} = 181\mu H$$

As for the buck converter, the output voltage ripple can be calculated as:
$$\Delta v_c = \frac{(V_d - V_o) \cdot D}{8 \cdot f_{sw}^2 \cdot L \cdot C} \rightarrow C \ge \frac{(V_{sec} - V_o) \cdot D}{8 \cdot f_{sw}^2 \cdot L \cdot \Delta v_c} = \frac{(130V - 54V) \cdot 0.417}{8 \cdot 100kHz^2 \cdot 170\mu H \cdot 20mV} = 116\mu F$$

$$\Delta v_c = \frac{(V_d - V_o) \cdot D}{8 \cdot f_{sw}^2 \cdot L \cdot C} \rightarrow C \ge \frac{(V_{sec} - V_o) \cdot D}{8 \cdot f_{sw}^2 \cdot L \cdot \Delta v_c} = \frac{(144V - 54V) \cdot 0.375}{8 \cdot 100kHz^2 \cdot 181\mu H \cdot 20mV} = 116\mu F$$

4) For the forward converter in (3), a new transformer shall be designed. You have two different E13/6/3-cores made of material 3C90 to choose between; a core with 0.25mm airgap and a core without airgap (see attached datasheet). Calculate the primary magnetizing inductance for both cores if $N_1 = 27$ with both the A_L-value and the reluctance of the core. Which core is most suitable in a forward transformer? Why? (3p)

The inductance for each core is calculated with the specified A_L-value (which is the same for both the core with center hole and the core without center hole):

$$L_{gapped} = A_L N^2 = 63 \cdot 27^2 = 46\mu H$$

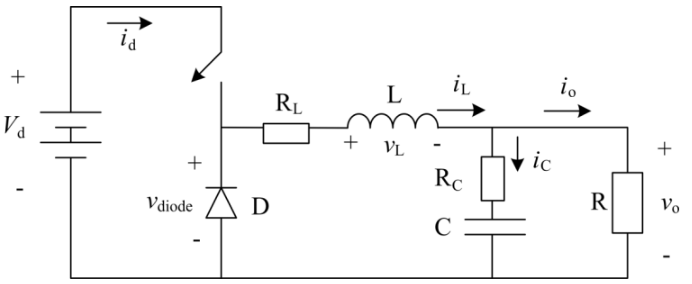
$L_{ungapped} = A_L N^2 = 730 \cdot 27^2 = 532\mu H$

The inductance can also be calculated by first calculating the reluctance of the core. If the air gap is considered, the majority of the reluctance lies within the air gap, hence can the core be neglected in this case.

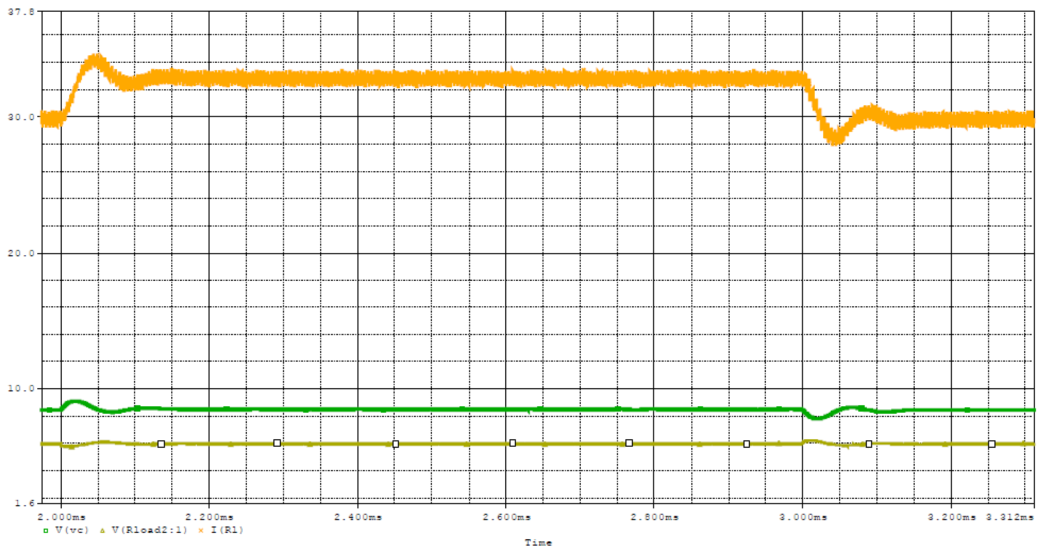
$$L = \frac{N^2}{\mathfrak{R}} = \begin{cases} L_{ungapped} = \dfrac{27^2}{l_e/\mu_r\mu_0 A} = \dfrac{27^2}{27.8mm/1590 \cdot 4\pi e^{-7} \cdot 10.1mm^2} = 529\mu H \\ L_{gapped} = \dfrac{27^2}{l_g/\mu_0 A} = \dfrac{27^2}{0.25mm/4\pi e^{-7} \cdot 10.1mm^2} = 37\mu H \\ L_{gapped} = \dfrac{27^2}{l_g/\mu_0 A} = \dfrac{27^2}{27.8mm/138 \cdot 4\pi e^{-7} \cdot 10.1mm^2} = 46\mu H \end{cases}$$

The transformer in the forward converter is used as a transformer (not to be confused with the flyback transformer which works as an energy storage device). A high magnetizing inductance gives lower ripple in the magnetizing current which means that the losses will decrease. So for thisw case, a transformer without air gap is preferable.

5) The buck converter below is used with real components (parasitic elements are included) and a controller circuit that keeps the output voltage constant. Explain thoroughly what happens if a load step (e.g. sudden increase/decrease of the output current) is applied on the output. Also, explain the effect of the parasitic resistances (R_L and R_C) on the transfer function of the power stage ($T_p(s)$). (4p)



The current suddenly increases at t=2ms which gives a reduced output voltage due to increased losses in the converter. This is detected by the controller which increases the dutycycle in order to keep the output voltage constant.



The transfer function of the power stage can be written on the form of a second order system:

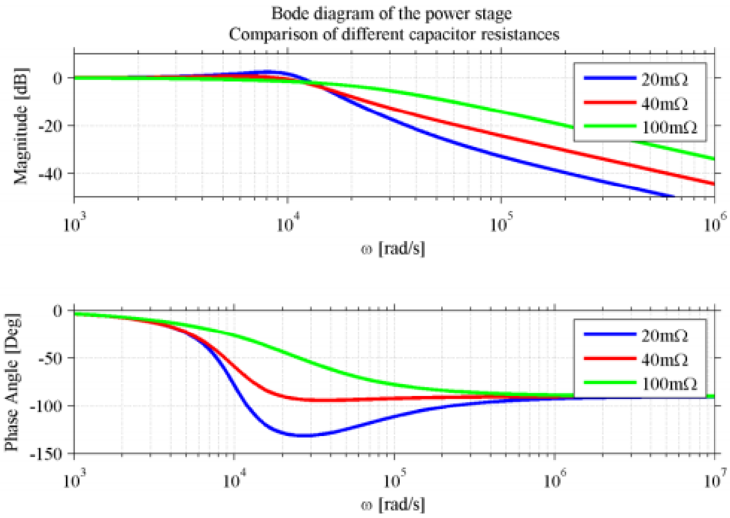
$$T_p(s) = \frac{1/R_C C}{1/R_C C} \cdot \frac{V_d \cdot \omega_0^2 \cdot (1 + sR_C C)}{s^2 + 2\zeta\omega_0 s + \omega_0^2} = V_d \frac{\omega_0^2}{\omega_z} \cdot \frac{s + \omega_z}{s^2 + 2\zeta\omega_0 s + \omega_0^2}$$

where

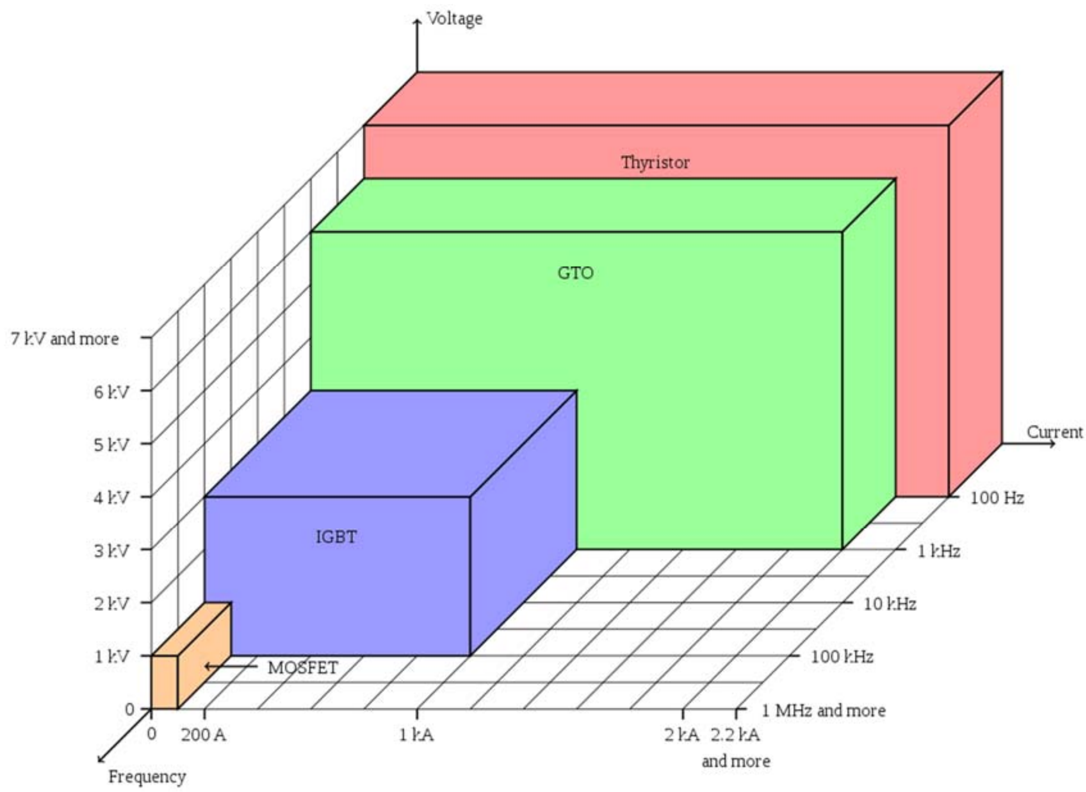
$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad \omega_z = \frac{1}{R_C C} \qquad \zeta = \frac{1}{2RC\omega_0} + \frac{R_C + R_L}{2L\omega_0}$$

Note that by inserting an equivalent series resistor in the capacitor (ω_z), a zero is inserted in the transfer function of the power stage. Also, the series resistance in the inductor (R_L) helps to increase the damping of the system since it is present in the damping term (ζ).

Since both the capacitor ESR (R_C) and the inductor resistance are included in the damping term (ζ), they will affect the performance of the converter. If these stray elements are increased, the damping of the system will increase.



6) In the question marks in graph below, name which component that is suitable for each corresponding power level (4p)



7) A single phase inverter is operating in square wave mode with a load that consists of an inductor ($L = 100mH$) in series with a sinusoidally shaped back-emf voltage source ($e_o = \sqrt{2} \cdot E_o \cdot \sin(\omega_1 t)$). The output fundamental voltage ($V_{o(1)}$) has a frequency of 50Hz and

the same amplitude and phase as the back-emf. The peak ripple in the output current is 2A, shown in the figure below. Calculate the resulting DC-link voltage (V_d). (4p)

This task can be solved in an analogous way as for the three-phase inverter operating in square-wave mode.

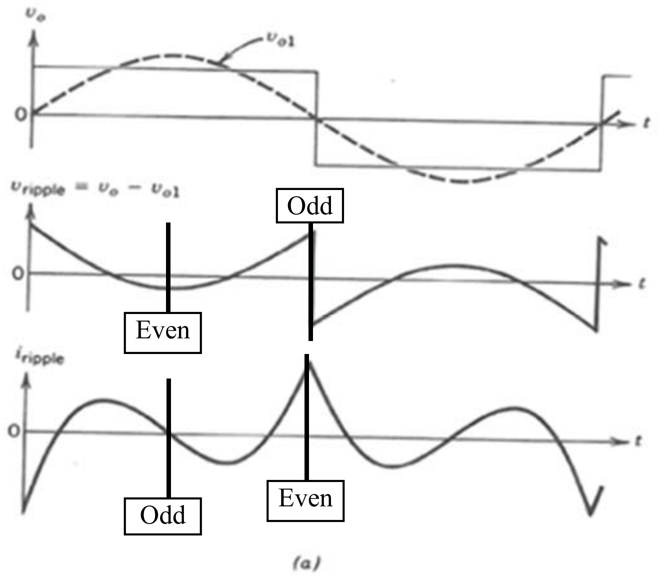


Figure 8-19 Ripple in the inverter output: (*a*) square-wave

The current is formed by the voltage applied over the load inductor. Due to the sinusoidal-shaped back-emf of the load, the ripple voltage will be applied over the inductor.

$$v_{o(ripple)} = v_o - v_{o(1)}$$

Since the ripple voltage is even at π/2 and odd at π, the ripple current must be odd at π/2 and even at π. The current ripple can be calculated by integrating the ripple voltage from T/4 to T/2.

In this interval $v_o = V_d$and the fundamental component can be calculated as (odd and half-wave):

$$b_n = \frac{4}{\pi}\int_0^{\pi/2} V_d \sin(n\theta)d\theta = -\frac{4}{\pi}\frac{V_d}{n}\left[\cos(n\theta)\right]_0^{\pi/2} = \frac{4}{\pi}\frac{V_d}{n}(1-\underbrace{\cos(n\frac{\pi}{2})}_{=0\ for\ odd\ n}) = \frac{4}{\pi}\frac{V_d}{n}$$

So $\hat{v}_{o(1)} = \frac{4V_d}{\pi}$

$$i_{o(ripple)}(\theta) = \underbrace{i_{o(ripple)}\left(\frac{\pi}{2}\right)}_{=0} + \frac{1}{\omega L}\int_{\pi/2}^{\pi} v_{o(ripple)}(\omega t)d\omega t = \frac{1}{\omega L}\int_{\pi/2}^{\pi}\left(V_d - \hat{V}_{o(1)}\sin(\omega t)\right)d\omega t =$$

$$= \frac{1}{2\pi \cdot 50Hz \cdot 100mH}\int_{\pi/2}^{\pi}\left(V_d - \frac{4V_d}{\pi}\cdot\sin(\omega t)\right)d\omega t = \frac{1}{\omega L}\left[V_d \cdot \omega t + \frac{4V_d}{\pi}\cdot\cos(\omega t)\right]_{\pi/2}^{\pi} =$$

$$= \frac{1}{2\pi \cdot 50Hz \cdot 100mH}\left(V_d \cdot \pi + \frac{4V_d}{\pi}\cdot(-1) - V_d \cdot \frac{\pi}{2} - \frac{4V_d}{\pi}\cdot 0\right) =$$

$$= \frac{1}{2\pi \cdot 50Hz \cdot 100mH}\left(V_d \cdot \frac{\pi}{2} - \frac{4V_d}{\pi}\right) = 2A$$

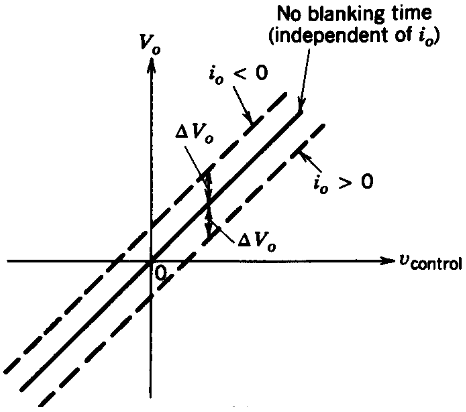
$$V_d = \frac{2\pi \cdot 50Hz \cdot 100mH \cdot 2A}{\pi/2 - 4/\pi} = 211V$$

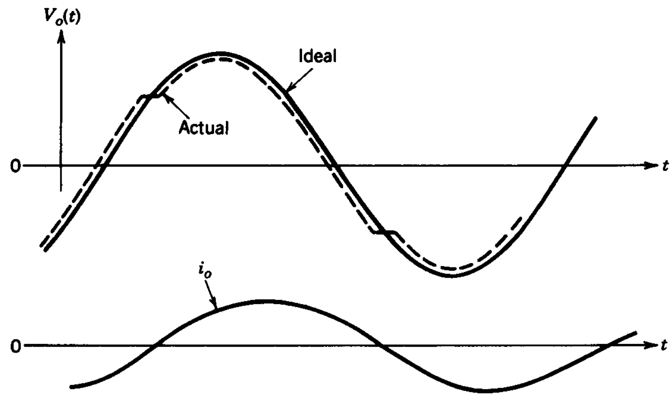
8) Consider a single phase inverter operating in PWM mode where the output current is sinusoidal and lagging the voltage. Why is blanking time needed? How will the blanking time affect the output current and voltage? Explain by e.g. drawings and harmonic content. (4p)

Blanking time is a short time period where both switches in one phase leg are turned off at the same time. This is needed to make sure that the source is not short-circuited due to the non-ideal switches.

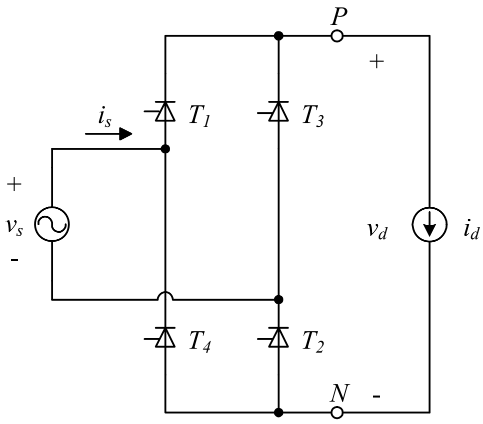
For a positive output current, the output voltage will be increased slightly due to the blanking time and for a negative output current, the output voltage will be decreased slightly.

The effect is seen in the output voltage when i_o has a zero crossing, there will be a notch in the voltage which results in low order harmonics (3:d, 5:th and so on) in the inverter output.



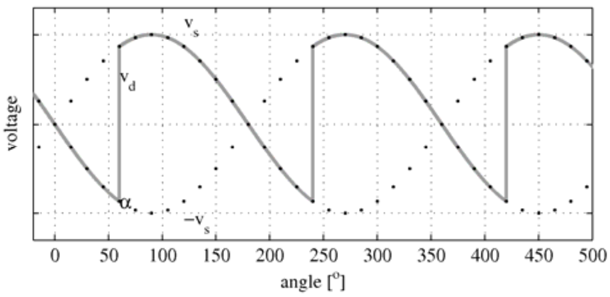


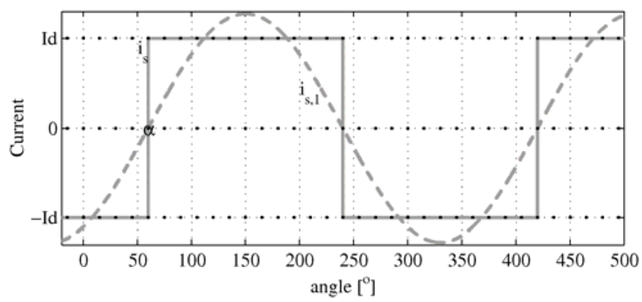
9) Consider the single phase thyristor rectifier below.



The input voltage (v_s) is a sinusoidal with an amplitude of 200V and a frequency of 50Hz. The delay angle (α) is 60° and the DC-side current (I_d) is constant current of 10A. Draw the output voltage waveform (v_d) and calculate the average value V_d. (3p)

The input voltage (v_s) and the output voltage (v_d) can be drawn as:





The average output voltage with delay angle 60° can be calculated as:

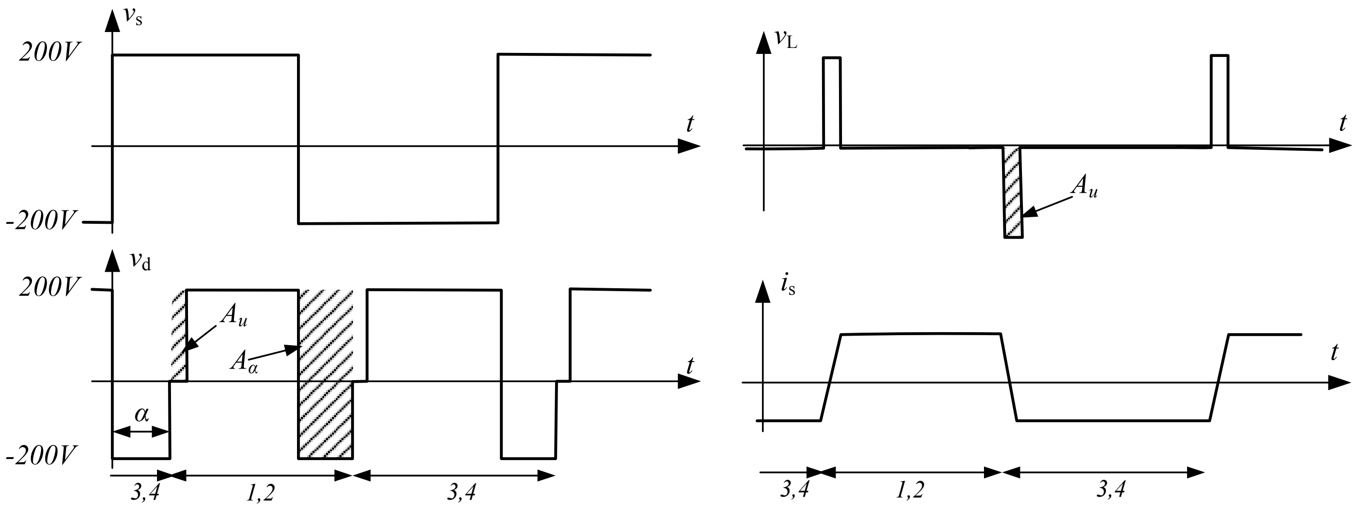
$$V_d = \frac{1}{T}\int_0^T v_d(t)dt = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha}\sqrt{2}V_s \sin(\theta)d\theta = \frac{\sqrt{2}V_s}{\pi}\left[-\cos(\theta)\right]_{\alpha}^{\pi+\alpha} = \frac{\sqrt{2}V_s}{\pi}\left(-\cos(\pi+\alpha)+\cos(\alpha)\right) =$$

$$= \left[\cos(\pi+\alpha) = \underbrace{\cos(\pi)}_{=-1}\cos(\alpha) - \underbrace{\sin(\pi)}_{=0}\sin(\alpha)\right] = \frac{\sqrt{2}V_s}{\pi}2\cos(\alpha)$$

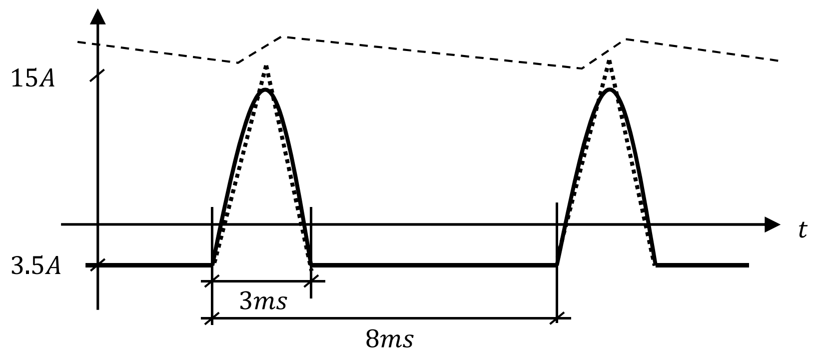
$$V_d = \frac{\sqrt{2}\cdot v_s}{\pi}2\cos\alpha = \frac{\sqrt{2}\cdot 200V}{\pi}2\cos 60° = 90V$$

10) The single phase thyristor rectifier in (9) is now fed with an input voltage that is square wave shaped with an amplitude of 200V and a frequency of 50Hz. If the source inductance (L_s) is considered, draw the output voltage (v_d), the voltage over the source inductance (L_s) and the source current (i_s) for the delay angle $\alpha = 30°$. (4p)

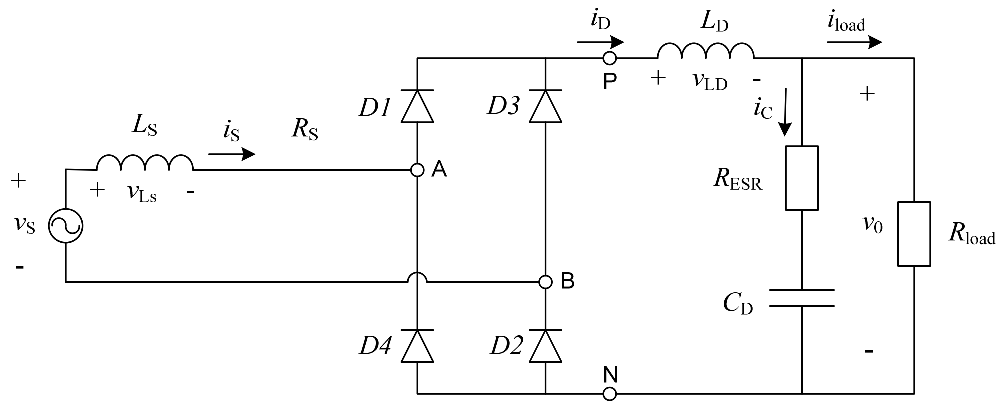
For the source current, the current increase during the commutation will be linear since the voltage applied over the inductance will be a constant voltage.



11) A single phase diode rectifier is used with a voltage stiff DC-side. The output voltage (dashed line, not to scale) and the capacitor current are depicted below.



The capacitor current is sinusoidal shaped during $3ms$. For reasons of simplicity, the current can be approximated with a triangular shape (see dotted curve) instead. Based on the two attached datasheets, select a suitable diode and calculate the resulting component temperature. Assume that the ambient temperature is $60°C$. (5p)



The current through one diode will consist of one pulse per 55Hz, i.e. half the cpacitor current. In order to calculate the power dissipation in a diode, the average current through each component needs to be calculated.

$$I_{D1(AVG)} = \sqrt{\frac{1}{16ms}\int_0^{16ms} i_{D1}\,dt} = \sqrt{\frac{1}{16ms}\left(\int_0^{1.5ms} i_{D1}\,dt + \int_{1.5ms}^{3ms} i_{D1}^2\,dt + \int_{3ms}^{16ms} 0A\,dt\right)} =$$

$$I_{D1(AVG)} = \sqrt{\frac{1}{16ms}\left(\frac{1.5ms}{1.5ms}\int_0^{1.5ms} i_{D1}\,dt + \frac{1.5ms}{1.5ms}\int_{1.5ms}^{3ms} i_{D1}\,dt + \int_{3ms}^{16ms} 0A\,dt\right)} =$$

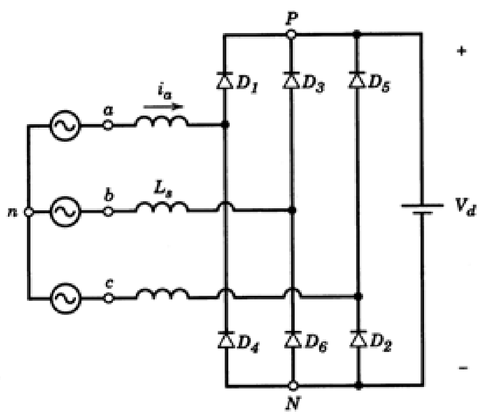
$$= \sqrt{\frac{1.5ms}{16ms\cdot 6}(0A + 4\cdot 9.25A + 18.5A) + \frac{1.5ms}{16ms\cdot 6}(18.5A + 4\cdot 9.25A + 0A) + \int_{3ms}^{16ms} 0A\,dt}$$

$$= \sqrt{\frac{1.5ms}{16ms\cdot 6}(55.5) + \frac{1.5ms}{16ms\cdot 6}(55.5) + 0} = 1.31A$$

$P_{D1} = V_F \cdot I_{D1(AVG)} = 3.9V \cdot 1.31A = 5.11W$
$P_{D1} = V_F \cdot I_{D1(AVG)} = 1.1V \cdot 1.31A = 1.44W$

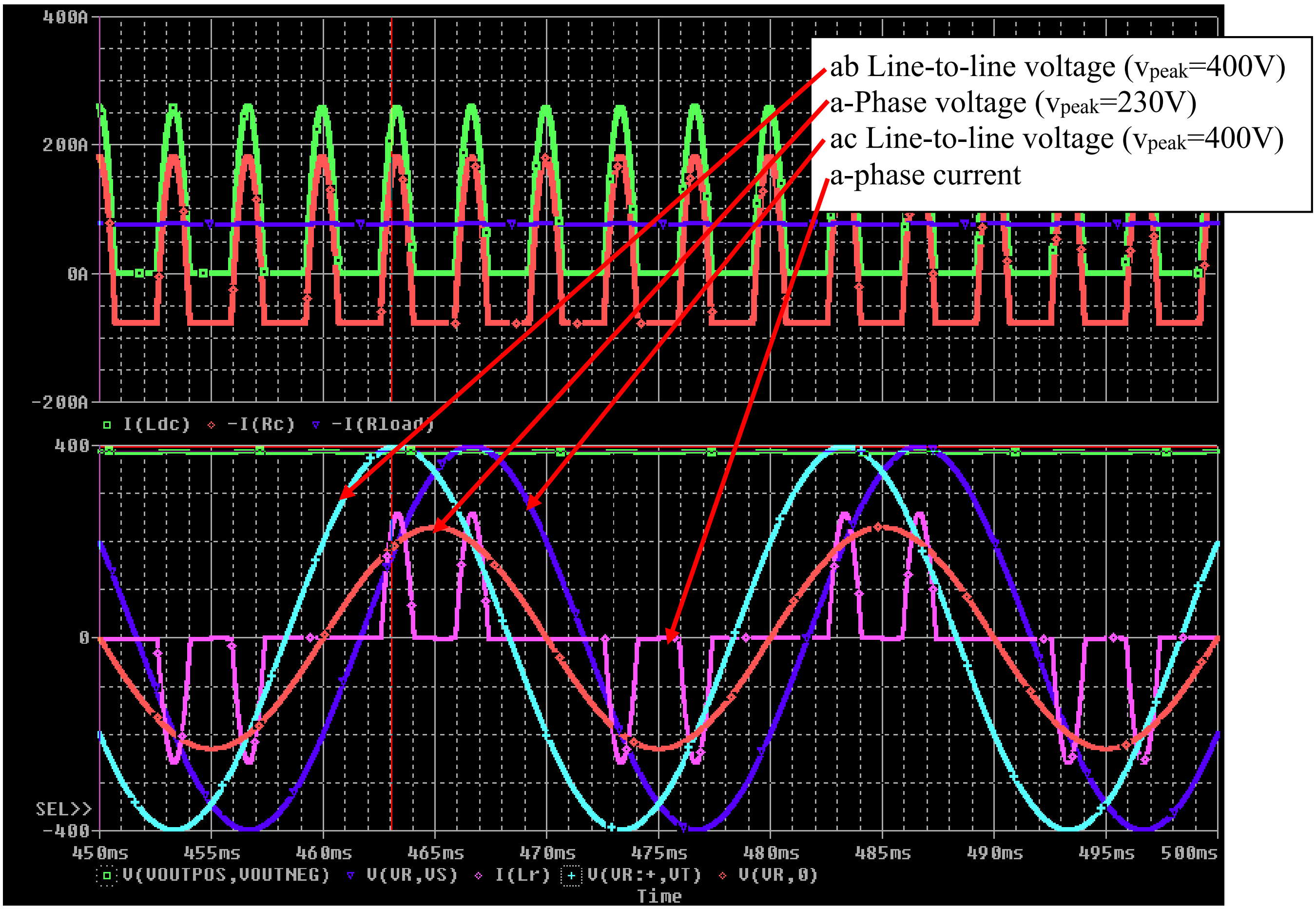
$T_j = P_{D1}R_{thJA} + T_A = 5.11W \cdot 15.9°C/W + 60°C = 115°C$ <- too hot!
$T_j = P_{D1}R_{thJA} + T_A = 1.44W \cdot 4.9°C/W + 60°C = 67°C$ <- OK temperature!

12) The three phase diode rectifier below is used with a voltage stiff DC-link and a negligible source inductance. The system operates with $50Hz$ and $v_a = v_b = v_c = 230V$ peak voltage. Draw the phase voltages (v_a, v_b, v_c), the resulting line-to-line voltage between phase a and b (v_{ab}) and the line current i_a. Clearly state the amplitudes and phase shifts between the voltages. The exact values of the line current are not needed. (4p)



Current is drawn from the voltage source as long as the input voltage is higher than the output voltage. Note that this happens two times for each phase, when the line-to-line voltages (v_{ab} and v_{ac}) are higher than the output voltage, a current is drawn from the source. This can be seen as two pulses in the middle of the R-phase voltage.

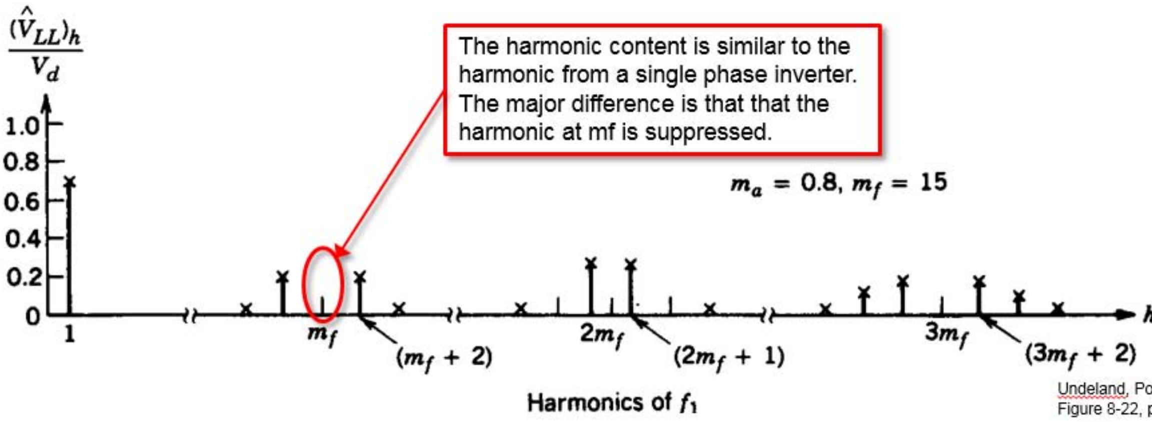
Points are given if the answer shows a difference in amplitude and phase (30°) between the phase and line-to-line voltages. To score full points, the correct phase current has to be drawn.



13) For a three phase inverter operating in PWM-mode, sketch the resulting harmonic spectrum for $m_a = 0.8$ and $m_f = 15$. Mark the amplitudes for the specified frequencies (and sidebands) in the diagram. (4p)

The harmonics in the line-to-line voltage are of concern

If m_f is selected to be odd and a multiple of three, the harmonics at m_f (and odd multiples of m_f) will disappear



Undeland, Power Electronics
Figure 8-22, page 227

Formulas for Examination in Power Electronic Converters (ENM060)

Table 3-1 Use of Symmetry in Fourier Analysis

Symmetry	*Condition Required*	a_h and b_h
Even	$f(-t) = f(t)$	$b_h = 0 \quad a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$
Odd	$f(-t) = -f(t)$	$a_h = 0 \quad b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$
Half-wave	$f(t) = -f(t + \frac{1}{2}T)$	$a_h = b_h = 0$ for even h $a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$ for odd h $b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$ for odd h
Even quarter-wave	Even and half-wave	$b_h = 0$ for all h $a_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\cos(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$
Odd quarter-wave	Odd and half-wave	$a_h = 0$ for all h $b_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\sin(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$

Definition of RMS-value:

$$F_{RMS} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} f(t)^2 dt}$$

Definition of RMS-value with Fourier-series:

$$F_{RMS} = \sqrt{F_0^2 + \sum_{n=1}^{\infty} F_n^2} = \sqrt{\left(\frac{a_0}{2}\right)^2 + \sum_{n=1}^{\infty}\left(\frac{\sqrt{a_n^2 + b_n^2}}{\sqrt{2}}\right)^2}$$

$$\sin^2(\alpha) + \cos^2(\alpha) = 1$$

$$\sin(\alpha + \beta) = \sin(\alpha)\cos(\beta) + \cos(\alpha)\sin(\beta) \qquad \sin(\alpha - \beta) = \sin(\alpha)\cos(\beta) - \cos(\alpha)\sin(\beta)$$

$$\cos(\alpha + \beta) = \cos(\alpha)\cos(\beta) - \sin(\alpha)\sin(\beta) \qquad \cos(\alpha - \beta) = \cos(\alpha)\cos(\beta) + \sin(\alpha)\sin(\beta)$$

$$\sin(\alpha)\sin(\beta) = \frac{1}{2}\left(\cos(\alpha - \beta) - \cos(\alpha + \beta)\right) \qquad \sin(\alpha)\cos(\beta) = \frac{1}{2}\left(\sin(\alpha - \beta) + \sin(\alpha + \beta)\right)$$

$$\cos(\alpha)\cos(\beta) = \frac{1}{2}\left(\cos(\alpha - \beta) + \cos(\alpha + \beta)\right)$$

$$\int \sin(ax)dx = -\frac{1}{a}\cos(ax), \quad \int x\sin(ax)dx = \frac{1}{a^2}\left(\sin(ax) - ax\cos(ax)\right), \quad \int \cos(ax)dx = \frac{1}{a}\sin(ax)$$

$$\int x\cos(ax)dx = \frac{1}{a^2}\left(\cos(ax) + ax\sin(ax)\right)$$

$$PF = \frac{P}{S} = \frac{V_s I_{s1}\cos\phi_1}{V_s I_s}, \quad DPF = \cos\phi_1, \quad \%THD_i = 100\frac{I_{dis}}{I_{s1}} = 100\frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} = 100\sqrt{\sum_{h\neq 1}\left(\frac{I_{sh}}{I_{s1}}\right)^2}$$

Electromagnetics

$$e = \frac{d}{dt}\psi \qquad \psi = N\phi \qquad \phi = BA \qquad R = \frac{l}{A\mu_r\mu_0} \qquad L = \frac{\Psi}{i}$$

$$NI = R\phi = mmf \qquad N\phi = LI \qquad L = A_L N^2 \qquad W = \frac{1}{2}LI^2$$

Simpson's rule

Let $f(x)$ be a polynomial of maximum third degree, this means

$$f(x) = a_1 + a_2 x + a_3 x^2 + a_4 x^3$$

For this function the integral can be calculated as

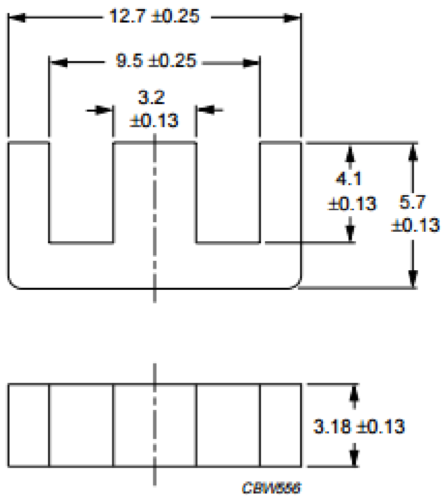
$$\frac{1}{T}\int_{t_0}^{t_0+T} f(x)dx = \frac{1}{6}\left(f(t_0) + 4f(t_0 + \frac{T}{2}) + f(t_0 + T)\right)$$

E cores and accessories E13/6/3

CORE SETS

Effective core parameters

SYMBOL	PARAMETER	VALUE	UNIT
$\Sigma(I/A)$	core factor (C1)	2.74	mm^{-1}
V_e	effective volume	281	mm^3
l_e	effective length	27.8	mm
A_e	effective area	10.1	mm^2
A_{min}	minimum area	10.1	mm^2
m	mass of core half	= 0.7	g



Dimensions in mm.

Fig.1 E13/6/3 core half.

Core halves

A_L measured in combination with a non-gapped core half, clamping force for A_L measurements, 8 ±4 N.

GRADE	A_L (nH)	μ_e	AIR GAP (µm)	TYPE NUMBER
3C90	63 ±5%	=138	= 250	E13/6/3-3C90-A63
	100 ±8%	= 219	=140	E13/6/3-3C90-A100
	160 ±8%	= 350	= 75	E13/6/3-3C90-A160
	250 ±20%	= 548	= 40	E13/6/3-3C90-A250
	315 ±20%	= 690	= 30	E13/6/3-3C90-A315
	730 ±25%	=1590	= 0	E13/6/3-3C90
3C92 des	540 ±25%	=1180	= 0	E13/6/3-3C92
3C94	730 ±25%	=1590	= 0	E13/6/3-3C94
3C96 des	660 ±25%	=1440	= 0	E13/6/3-3C96

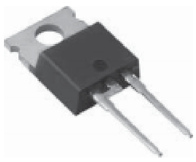
Diode 1:

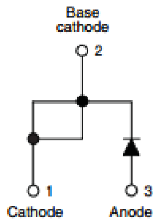
VS-HFA06TB120PbF, VS-HFA06TB120-N3

www.vishay.com

Vishay Semiconductors

HEXFRED®, Ultrafast Soft Recovery Diode, 6 A





TO-220AC

FEATURES

- Ultrafast and ultrasoft recovery
- Very low I_{RRM} and Q_{rr}
- Compliant to RoHS Directive 2002/95/EC
- Designed and qualified according to JEDEC-JESD47
- Halogen-free according to IEC 61249-2-21 definition (-N3 only)

RoHS COMPLIANT

HALOGEN FREE

BENEFITS

- Reduced RFI and EMI
- Reduced power loss in diode and switching transistor
- Higher frequency operation
- Reduced snubbing
- Reduced parts count

DESCRIPTION

VS-HFA06TB120... is a state of the art ultrafast recovery diode. Employing the latest in epitaxial construction and advanced processing techniques it features a superb combination of characteristics which result in performance which is unsurpassed by any rectifier previously available. With basic ratings of 1200 V and 6 A continuous current, the VS-HFA06TB120... is especially well suited for use as the companion diode for IGBTs and MOSFETs. In addition to ultrafast recovery time, the HEXFRED® product line features extremely low values of peak recovery current (I_{RRM}) and does not exhibit any tendency to "snap-off" during the t_b portion of recovery. The HEXFRED features combine to offer designers a rectifier with lower noise and significantly lower switching losses in both the diode and the switching transistor. These HEXFRED advantages can help to significantly reduce snubbing, component count and heatsink sizes. The HEXFRED VS-HFA06TB120... is ideally suited for applications in power supplies and power conversion systems (such as inverters), motor drives, and many other similar applications where high speed, high efficiency is needed.

PRODUCT SUMMARY	
Package	TO-220AC
$I_{F(AV)}$	6 A
V_R	1200 V
V_F at I_F	3.0 V
t_{rr} typ.	26 ns
T_J max.	150 °C
Diode variation	Single die

$$R_{thJA} = 15.9°C/W$$

ABSOLUTE MAXIMUM RATINGS

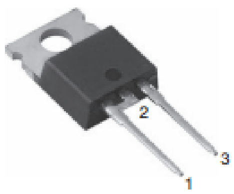
PARAMETER	SYMBOL	TEST CONDITIONS	VALUES	UNITS
Cathode to anode voltage	V_R		1200	V
Maximum continuous forward current	I_F	T_C = 100 °C	6	A
Single pulse forward current	I_{FSM}		80	
Maximum repetitive forward current	I_{FRM}		24	
Maximum power dissipation	P_D	T_C = 25 °C	62.5	W
		T_C = 100 °C	25	
Operating junction and storage temperature range	T_J, T_{Stg}		- 55 to + 150	°C

ELECTRIACL SPECIFICATIONS (T_J = 25 °C unless otherwise specified)

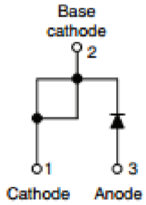
PARAMETER	SYMBOL	TEST CONDITIONS	MIN.	TYP.	MAX.	UNITS
Cathode to anode breakdown voltage	V_{BR}	I_R = 100 µA	1200	-	-	V
Maximum forward voltage	V_{FM}	I_F = 6.0 A	-	2.7	3.0	
		I_F = 12 A	-	3.5	3.9	
		I_F = 6.0 A, T_J = 125 °C	-	2.4	2.8	
Maximum reverse leakage current	I_{RM}	V_R = V_R rated	-	0.26	5.0	µA
		T_J = 125 °C, V_R = 0.8 x V_R rated	-	110	500	
Junction capacitance	C_T	V_R = 200 V	-	9.0	14	pF
Series inductance	L_S	Measured lead to lead 5 mm from package body	-	8.0	-	nH

Diode 2:

High Voltage, Input Rectifier Diode, 10 A



TO-220AC



FEATURES

- Very low forward voltage drop
- 150 °C max. operating junction temperature
- Designed and qualified according to JEDEC-JESD47
- Material categorization:
  For definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT
HALOGEN FREE Available

PRODUCT SUMMARY	
Package	TO-220AC
$I_{F(AV)}$	10 A
V_R	800 V to 1200 V
V_F at I_F	1.1 V
I_{FSM}	160 A
T_J max.	150 °C
Diode variation	Single die

APPLICATIONS

- Input rectification
- Vishay Semiconductors switches and output rectifiers which are available in identical package outlines

DESCRIPTION

High voltage rectifiers optimized for very low forward voltage drop with moderate leakage.

These devices are intended for use in main rectification (single or three phase bridge).

OUTPUT CURRENT IN TYPICAL APPLICATIONS			
APPLICATIONS	SINGLE-PHASE BRIDGE	THREE-PHASE BRIDGE	UNITS
Capacitive input filter T_A = 55 °C, T_J = 125 °C common heatsink of 1 °C/W	12.0	16.0	A

MAJOR RATINGS AND CHARACTERISTICS			
SYMBOL	CHARACTERISTICS	VALUES	UNITS
$I_{F(AV)}$	Sinusoidal waveform	10	A
V_{RRM}		800/1200	V
I_{FSM}		160	A
V_F	10 A, T_J = 25 °C	1.1	V
T_J		- 40 to 150	°C

VOLTAGE RATINGS			
PART NUMBER	V_{RRM}, MAXIMUM PEAK REVERSE VOLTAGE V	V_{RSM}, MAXIMUM NON-REPETITIVE PEAK REVERSE VOLTAGE V	I_{RRM} AT 150 °C mA
VS-10ETS08PbF, VS-10ETS08-M3	800	900	0.5
VS-10ETS12PbF, VS-10ETS12-M3	1200	1300	

ABSOLUTE MAXIMUM RATINGS				
PARAMETER	SYMBOL	TEST CONDITIONS	VALUES	UNITS
Maximum average forward current	$I_{F(AV)}$	T_C = 105 °C, 180° conduction half sine wave	10	A
Maximum peak one cycle non-repetitive surge current	I_{FSM}	10 ms sine pulse, rated V_{RRM} applied	135	
		10 ms sine pulse, no voltage reapplied	160	
Maximum I^2t for fusing	I^2t	10 ms sine pulse, rated V_{RRM} applied	91	A^2s
		10 ms sine pulse, no voltage reapplied	130	
Maximum $I^2\sqrt{t}$ for fusing	$I^2\sqrt{t}$	t = 0.1 ms to 10 ms, no voltage reapplied	1300	$A^2\sqrt{s}$

$$R_{thJA} = 4.9°C/W$$