Examination **ENM060 Power Electronic Converters**

Date and time Monday January 11th, 2016, 14:00 – 18:00

Responsible Teacher: Andreas Henriksson, tel. 0709-524924

Authorised Aids: Chalmers-approved calculator (Casio FX82..., Texas Instruments Ti-30... and Sharp EL-W531...)

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), January 12th 2016

Review of Exam February 9th and February 17th, 12:00-13:00.
Fredrik Lamms Room. Division of Electric Power Engineering (1st floor).

From February 18th 2016, 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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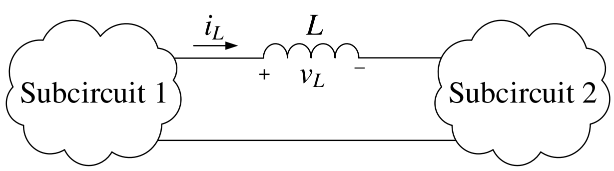
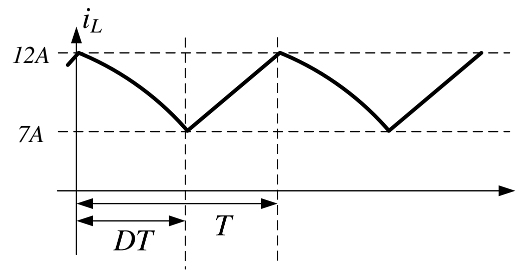
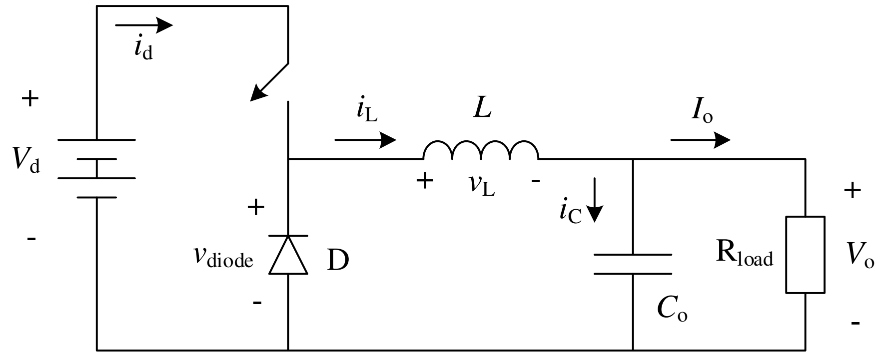
1) For the circuit below with $T = 30\mu s$ and $D = 0.6$, sketch the resulting voltage and calculate the inductance needed if the voltage applied over the inductor during $DT < t < T$ is $24V$. (3p)





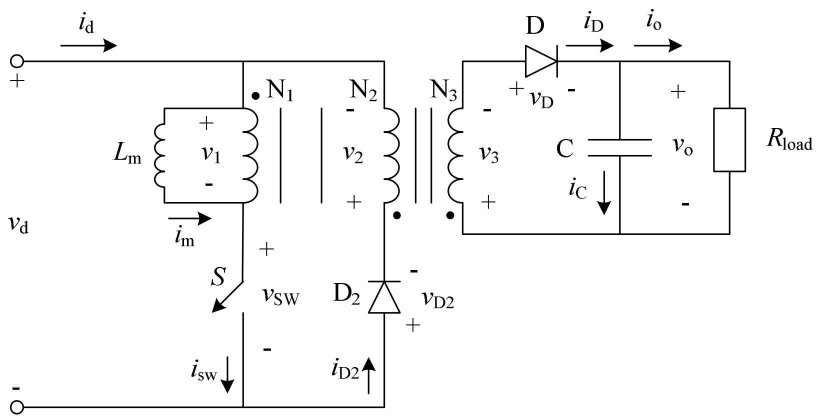
2) For the buck converter below, <u>derive</u> an expression for the ratio between the input and the output voltage if the converter is operating in CCM. (2p)



3) The buck converter in (2) is used with the circuit parameters and operating conditions below. Apply Simpsons formula and calculate the maximum power dissipation in the diode if $V_F = 0.63V$ is used. (5p)

$20V \le V_d \le 40V \qquad V_o = 12V \qquad L = 40\mu H \qquad f_s = 80kHz \qquad C_o = 330\mu F \qquad I_o = 7A$

4) For the flyback converter below, an LC-filter is applied to the input that smoothens the current drawn from the DC-source. Calculate the power dissipation in the input filter capacitor if $R_{ESR} = 80m\Omega$. Assume that the input filter is sufficiently large so that the current from the DC-source is a pure DC-current. (5p)



$L_m = 63\mu H \qquad C = 470\mu F \qquad V_d = 9V \qquad V_o = 24V \qquad f_{sw} = 100kHz \qquad I_o = 2.5A$

$(N_1 : N_2 : N_3) = (4 : 1 : 4)$

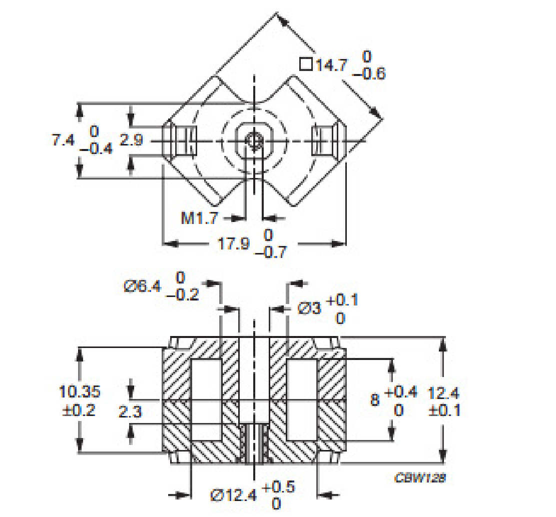
5) You shall design a transformer and you have two different RM6R-cores made of material 3D3 to choose between; a core with 0.7mm airgap and a core without airgap (see datasheet below). For the two cores, calculate the maximum allowed current with and without an airgap for $B_{max} = 380mT$ ($\mu_0 = 4\pi \cdot 10^{-7}$). Also, exemplify for which converter topologies transformers with and without airgaps can be used. (4p)

CORE SETS

Effective core parameters

SYMBOL	PARAMETER	VALUE	UNIT
$\Sigma(I/A)$	core factor (C1)	0.810	mm^{-1}
V_e	effective volume	810	mm^3
l_e	effective length	25.6	mm
A_e	effective area	32.0	mm^2
A_{min}	minimum area	23.8	mm^2
m	mass of set	≈ 4.5	g

$N=33$



Dimensions in mm.

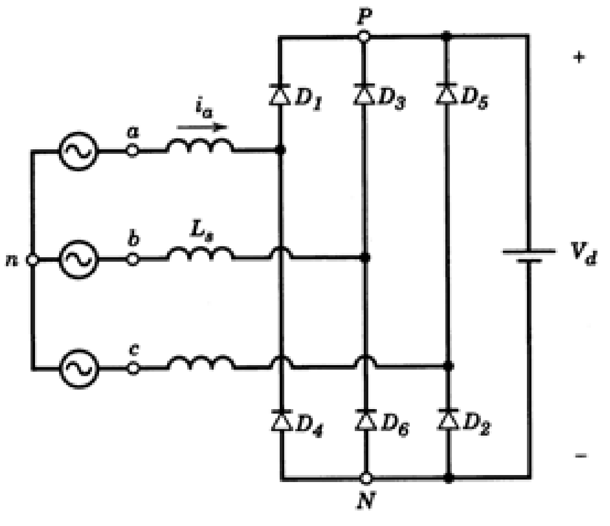
Fig.1 RM6R core set.

Core sets for filter applications

Clamping force for A_L measurements, 40 ±20 N.

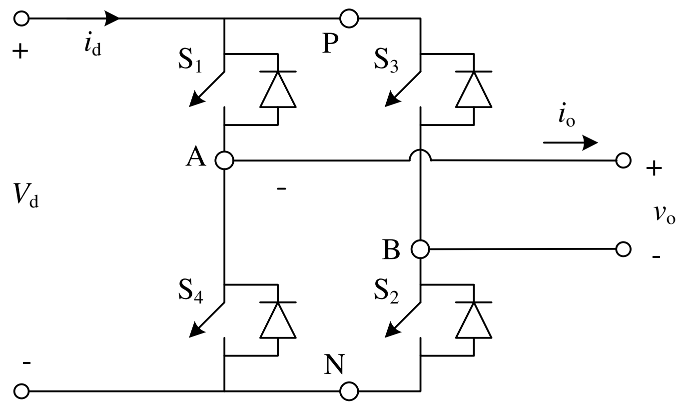
GRADE	A_L (nH)	μ_e	TOTAL AIR GAP (μm)	TYPE NUMBER (WITH NUT)	TYPE NUMBER (WITHOUT NUT)
3D3 sup	40 ±3%	≈ 26	≈ 1200	RM6R-3D3-E40/N	RM6R-3D3-E40
	63 ±3%	≈ 41	≈ 700	RM6R-3D3-E63/N	RM6R-3D3-E63
	100 ±3%	≈ 65	≈ 400	RM6R-3D3-E100/N	RM6R-3D3-E100
	160 ±3%	≈ 103	≈ 200	RM6R-3D3-A160/N	RM6R-3D3-A160
	1000 ±25%	≈ 650	≈ 0	−	RM6R-3D3

6) The three phase diode rectifier depicted 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 voltage in phase *a* (v_{an}), the resulting line-to-line voltage between phases a, b and c (v_{ab} and v_{ac}) and the phase current (i_a). Clearly state the amplitudes and phase shifts between the voltages. An exact value of the line current is not needed. (4p)



7) **The diode rectifier in (6) is now connected to a grid with a source inductance. How will this affect the power factor (PF) and the displacement power factor (DPF)? Exemplify with e.g. graphs and Fourier components. (3p)**

8) **For the single phase inverter below, determine the 3 first harmonic components of the load voltage for square-wave operation. (4p)**

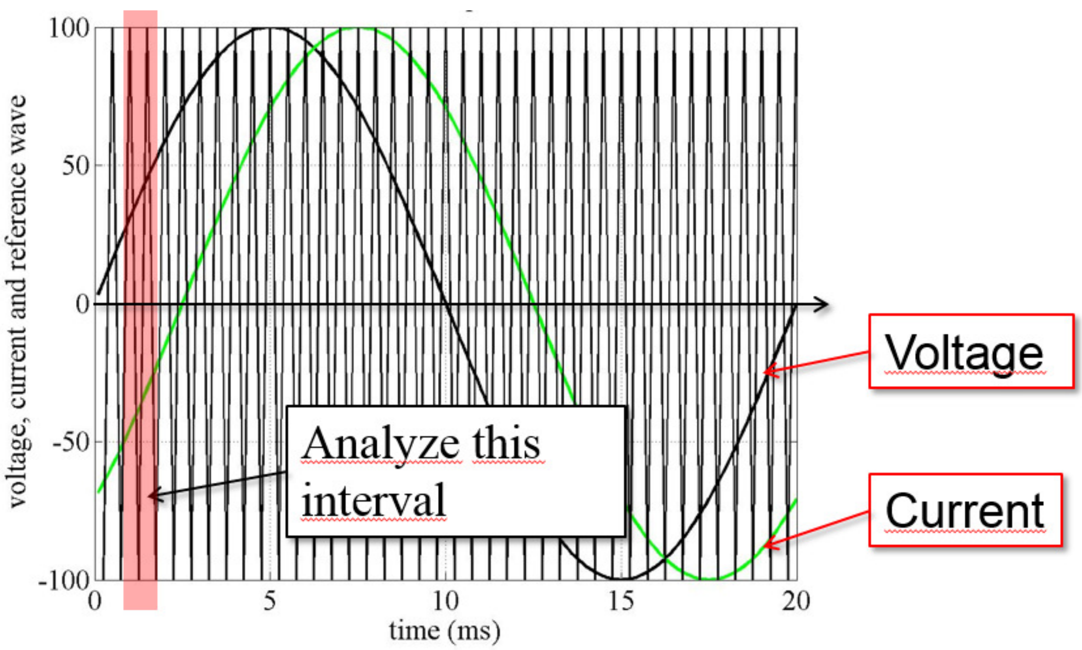


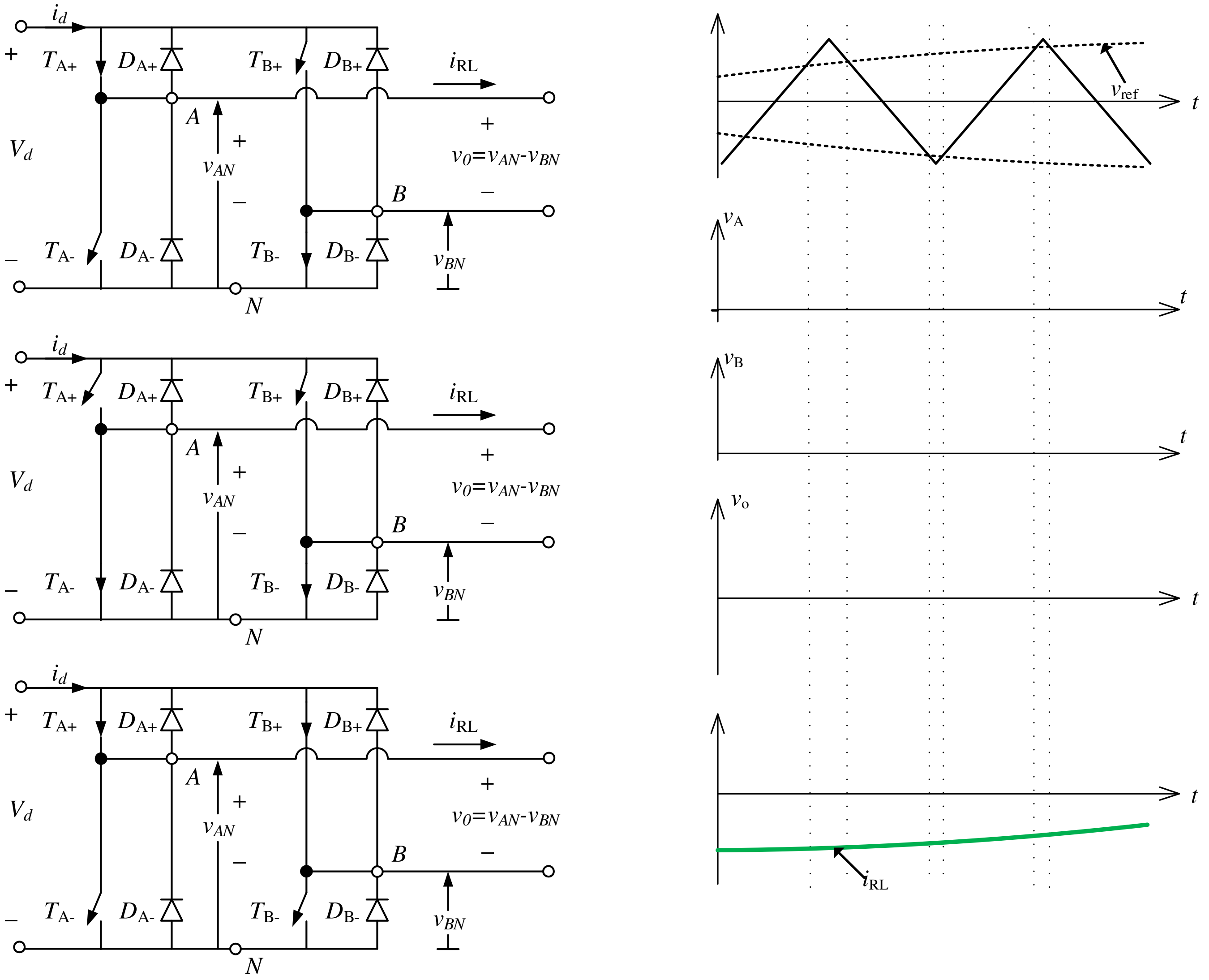
Nominal values for square wave inverter

Source voltage	U_s = 200V
Load inductance	L = 10mH
Load resistance	R = 2Ω
Fundamental frequency	$f_{s,1}$ = 50Hz

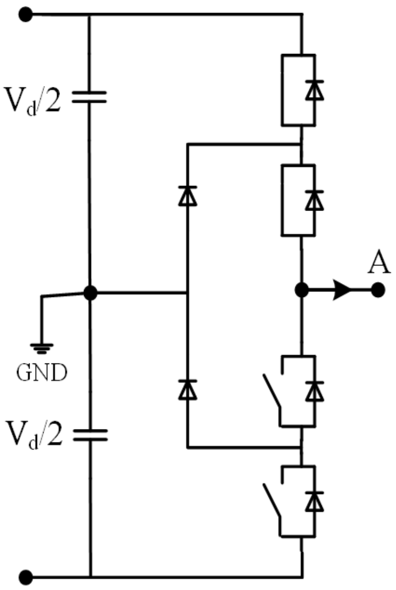
9) **If the single phase inverter in (8) is operated with PWM bipolar switching in the linear range ($m_a \leq 1$). What is the lowest DC-link voltage that is required in order to obtain a fundamental frequency voltage component of 180V$_{RMS}$? (2p)**

10) **The single phase inverter in (8) is operated in PWM-mode with unipolar switching. For the shaded time interval (the fundamental frequency component of the output voltage is positive and the output current is negative), draw the voltages (v_A, v_B, v_o) in the empty graphs. Draw also the current paths in the 3 circuits and clearly mark during which time interval each current path is valid and which components (e.g. switches or diodes) that carry the current. (3p)**



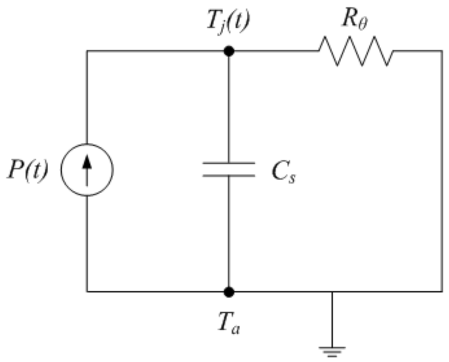


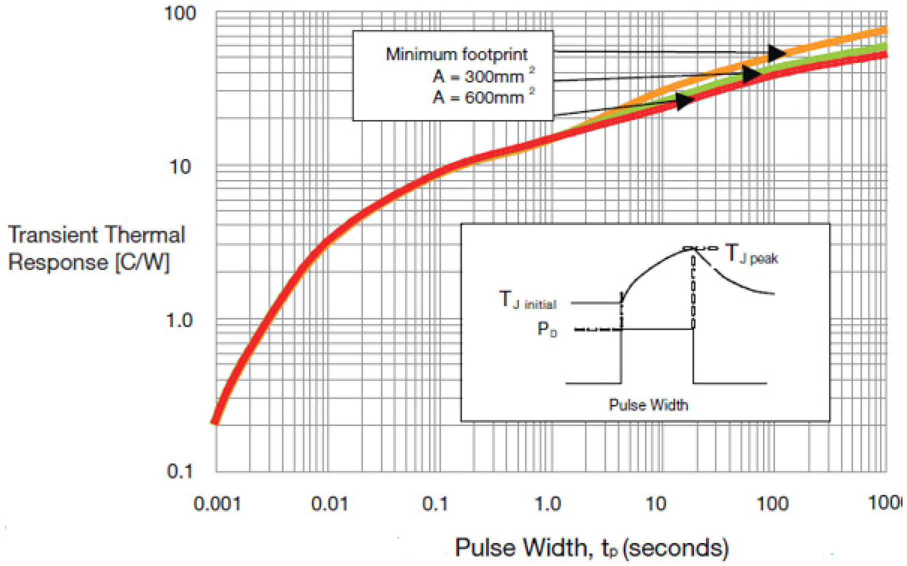
11) Consider a neutral point diode clamped (NPC) 3-level inverter that consists of three parallel phase legs as the one depicted below. Draw the resulting mid-point voltages ($v_{AGND}, v_{BGND}, v_{CGND}$) and the resulting voltage (v_{An}) that is applied over a *y*-connected load (phase voltage). (4p)

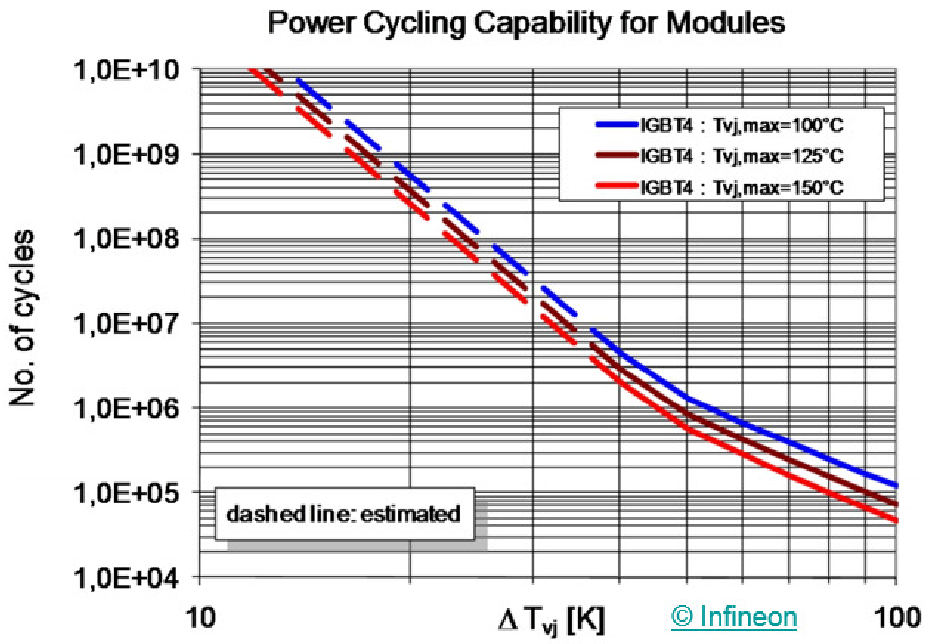


$$v_{An} = \frac{2}{3}v_{AGND} - \frac{1}{3}(v_{BGND} + v_{CGND})$$

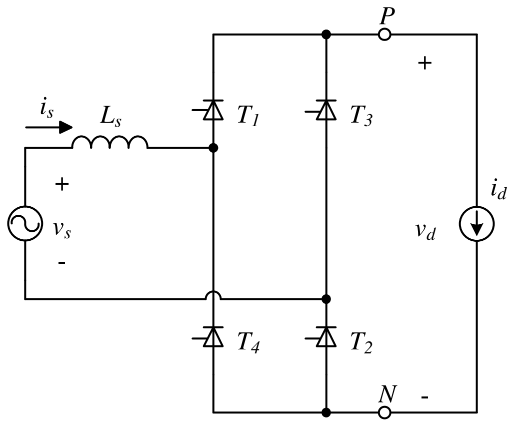
12) **The dynamic thermal characteristics of a power module can be represented with the thermal network below. The system is exposed to a pulsed power source where each pulse is 3W and lasts for 10seconds. After the power pulse, the module is cooled to the previous temperature. If the module is assumed to operate in an ambient temperature of 100ºC and with the minimum footprint, how many thermal cycles will the module survive before it breaks down? Due to which mechanism will it break down? (3p)**







13) **Consider the single phase thyristor rectifier with source inductance below.**



If the input is a triangular wave shaped voltage with an amplitude of 100V (peak) at a frequency of 60 Hz, draw the output voltage waveform (v_d) and calculate the average value V_d if the delay angle (α) is 45° and the source inductance (L_s) is 2mH. Assume that the DC-side current (i_d) is constant 10A. (5p)

14) **What are the main benefits of using 12-pulse rectification in a three-phase thyristor application (e.g. a HVDC classic transmission line)? Exemplify with e.g. input current and output voltage. (3p)**

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

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