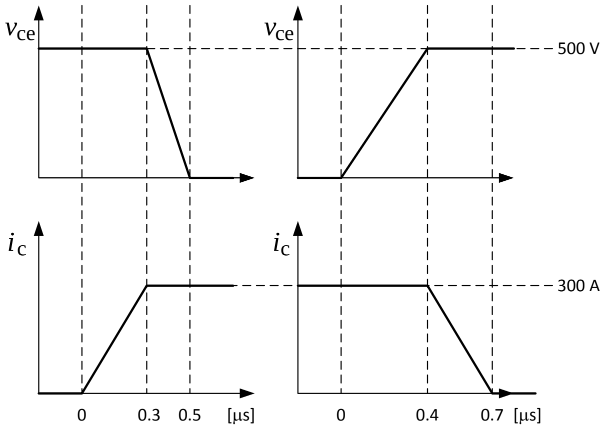
KTH Electrical Engineering

Additional Examination in **POWER ELECTRONICS** (EJ2300)
Tuesday, 8th of January 2013, 8:00 – 13:00 (Questions 9:00, 10:30, and 12:00)
Exam responsible: Hans-Peter Nee, 070 – 695 34 70

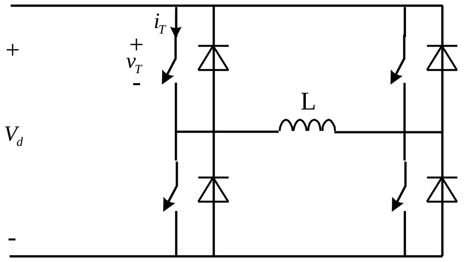
Permitted aid: Calculator, mathematical handbook, and three-phase paper.
The requirement to pass is 15 points. Problems 1–5 give 3 points each and problems 6–8 give 5 points each.
For full marks, the solutions have to be readable and *the line of thought has to be recognizable*!
Do not forget to scale axes of graphs!
Only one problem per paper! (Because different persons will mark different problems!)

1. A flyback converter operates in the continuous conduction mode. The input voltage is 289 V and the output voltage is 17 V. The input power is 289 W. Calculate the turns-ratio of the transformer if the duty ratio is 0,5.

2. In the figure below a turn-ON and a turn-OFF of an IGBT is sketched. Calculate the switching losses for a steady-state case when the switching frequency is 6 kHz.

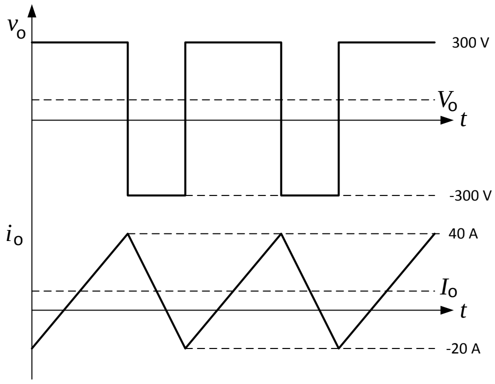


3. The single-phase inverter below is square-wave modulated with the frequency 1 kHz. It supplies a pure inductance of 1 mH. The input voltage V_d = 400 V. Find the fundamental content in the inductor current.



4. Two three-phase thyristor bridge converters are connected to the same grid, 3×400V (line-line), 50 Hz. One converter is feeding 20 kW to a motor at an armature voltage of 200V. The other converter is feeding 500 A to a very large inductance. The direct voltage of the second converter is almost zero. Calculate the total active and reactive power drawn from the grid.

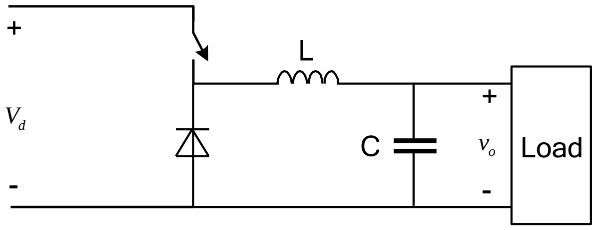
5. In the figure below the output quantities of a full-bridge dc-dc converter are shown. Draw the waveform of the instantaneous output power. All values at extreme points must be calculated and the "Y-axis" must be scaled such that the instantaneous power can be read from the graph. Also indicate the average output power in the graph.



6. A step-down converter (see below) is supplied from a car battery for which the voltage may vary between 8 and 14 V. The output voltage should be constant 6 V. The load current is always larger than 1 A and the switching frequency is 40 kHz.

a) 3p Under the assumption that C is large, find the required inductance L in order to keep the converter in continuous-conduction mode.

b) 2p Under the assumption that L = 100 μH, find the required capacitance C in order to keep the output voltage ripple below 0,1 V.



7. A three-phase full-bridge thyristor converter is supplied from V_{LL}=400 V, 50 Hz. It supplies a dc-motor consuming 10 A running at 1200 rad/s. The motor is modelled as an emf, $E_a = K_E \omega_m$, where $K_E = 0{,}3$ Vs/rad. There is a large smoothing inductor on the dc-side.

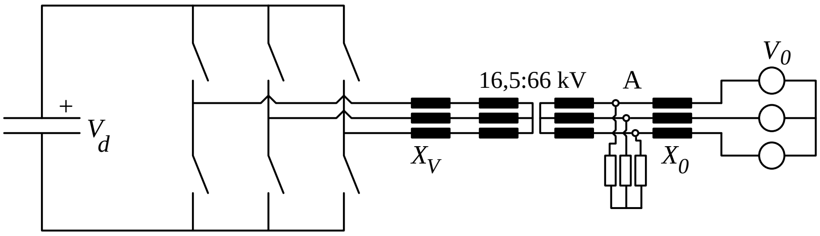
a) Determine the output voltage V_d. Find the firing angle α. Draw the direct voltage $v_d(t)$ and a voltage $v_{thy}(t)$ across one of the thyristors.

Assume that there are no losses in the dc-motor. Determine the produced torque?

b) Take into account that the supply actually has an internal inductance of 3 mH/phase, find the required firing angle to obtain the same speed.

8. A 66 kV grid feeds a resistive load that consumes 30 MW at a line-to-line voltage of 66 kV. The grid can be represented by a three-phase voltage source V_0 with the line-to-line voltage 66 kV with an internal impedance X_0 being entirely inductive. In case of short circuit in node A, the internal impedance consumes 100 Mvar.

When the resistive load is connected the voltage in node A drops to a value that is too low, and therefore a three-phase inverter used for reactive power compensation (STATCOM) is connected via a transformer with the turns ratio 4 and a 20 ohm reactor X_V . The control of the inverter makes sure that the voltage in node A becomes 66 kV and that V_d is 40 kV. Observe that the current that is fed into node A from the inverter is purely capacitive.



a) Draw a phasor diagram describing the voltage in node A, the internal voltage source of the grid, the voltage across the internal impedance of the grid, and the current from V_0 to node A. (1p)

b) Calculate the current from V_0 to node A. (2p)

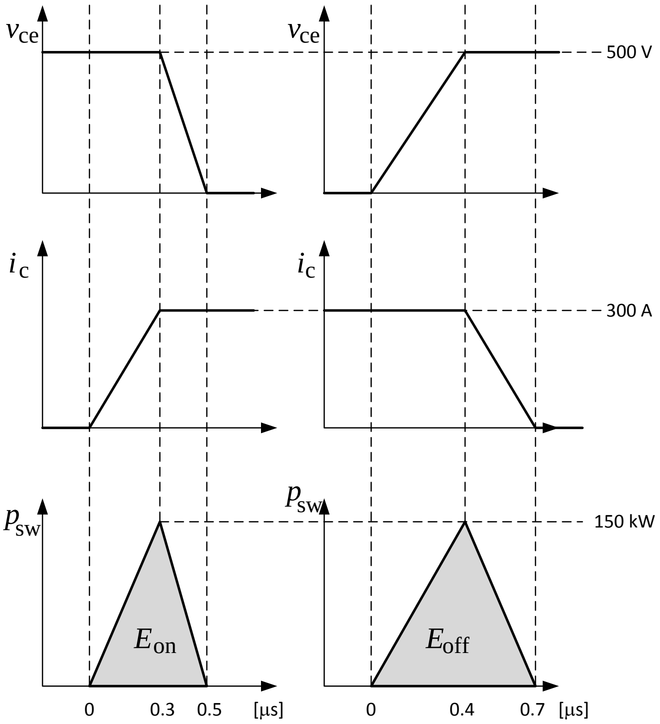
c) Calculate the amplitude modulation index of the three-phase inverter. (2p)

Solutions

1.

$$\left.\begin{array}{l} \left|\Delta\psi_1\right| = N_1 V_d \cdot \dfrac{T}{2} \\ \left|\Delta\psi_2\right| = N_2 V_o \cdot \dfrac{T}{2} \end{array}\right\} \Rightarrow N_1 V_d = N_2 V_o \;\; ; \;\; \frac{N_1}{N_2} = \frac{V_d}{V_o} = \frac{289}{17} = \underline{17}$$

2. The instantaneous power dissipation during the switching transients can be plotted along with the voltage and current waveforms:



The switching energies at turn-ON and turn-OFF are found to be:

$$E_{\mathrm{on}} = \frac{150000}{2}\cdot 0.5\cdot 10^{-6} = 37,5 \text{ mWs}; \quad E_{\mathrm{off}} = \frac{150000}{2}\cdot 0.7\cdot 10^{-6} = 52,5 \text{ mWs}$$

$$P_{\mathrm{sw}} = \left(E_{\mathrm{on}} + E_{\mathrm{off}}\right)\cdot f_{\mathrm{sw}} = \left(0,0375 + 0,0525\right)\cdot 6000 = \underline{540 \text{ W}}$$

3.

$$V_{L(1)} = 0,9\cdot V_d = 360 \text{ V}$$

$$I_{L(1)} = \frac{V_{L(1)}}{\omega L} = \frac{360}{2\pi\cdot 1000\cdot 1\cdot 10^{-3}} = \underline{57,3 \text{ A}}$$

4. Find α for the bridge feeding the motor. $V_{d\alpha} = 1,35\cdot V_{LL}\cdot\cos(\alpha) \Leftrightarrow \cos(\alpha) = \dfrac{V_{d\alpha}}{1,35\cdot V_{LL}} = 0,37037$

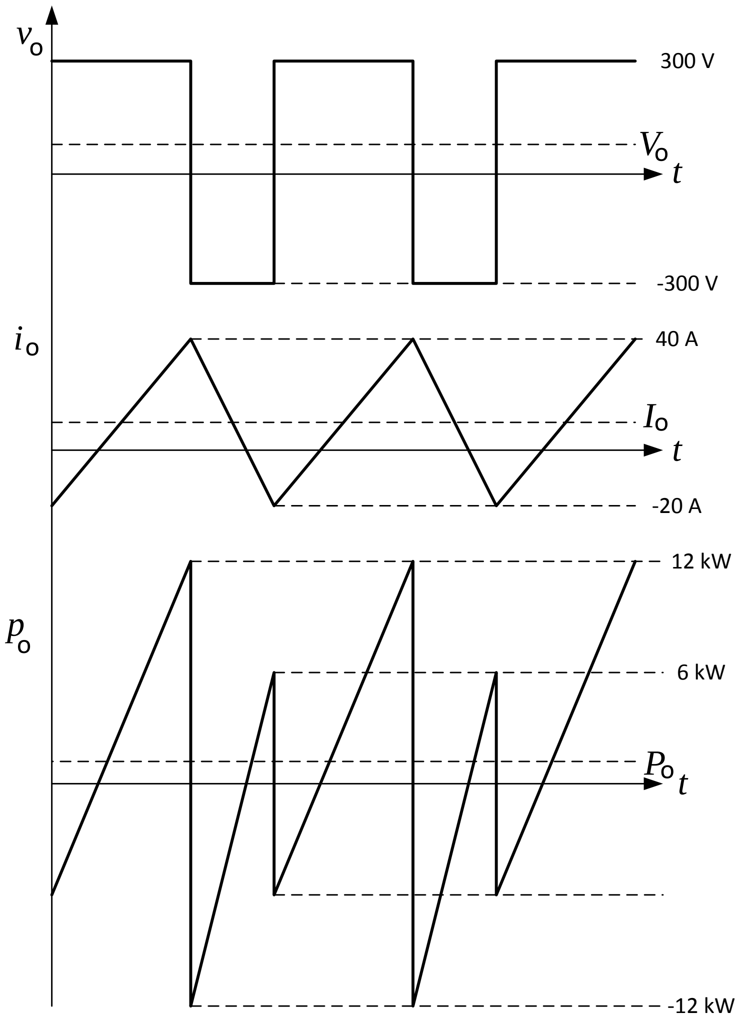
$$S_1\cdot\cos(\alpha) = P \Leftrightarrow S_1 = \frac{P}{\cos(\alpha)}; \quad Q_1 = S_1\cdot\sin(\alpha) = \frac{P\cdot\sin(\alpha)}{\cos(\alpha)} = \frac{20000\cdot\sqrt{1-\left(0,37037\right)^2}}{0,37037} = 50,16 \text{ kvar}$$

The other bridge draws a quasi-square current with the fundamental component:

$$I_1 = 0,78 \cdot 500 = 390 \text{ A} \Rightarrow \text{Q}=\sqrt{3} \cdot 400 \cdot 390 = 270,20 \text{ kvar}$$

$$P_{tot} = \underline{20 \text{ kW}} \quad Q_{tot} = 50,2 + 270,2 = \underline{320 \text{ kvar}}$$

5.



6, a) $V_d = 8 \ldots 14V$ $\quad \Delta I_L = \frac{DT_s}{L} V_d (1-D) = \frac{1}{fL} V_o (1-D)$ worstcase $D = \frac{6}{14}$

$I_{LB} = 1 \Rightarrow \Delta I_L = 2 \quad \Rightarrow \quad \underline{L > 43 \mu H}$

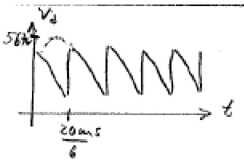
b) $\Delta V_o = \frac{\Delta Q}{C} = \ldots = \frac{T}{8C} \cdot \frac{V_o}{L} (1-D) T_s$, again worstcase $D = \frac{6}{14}$

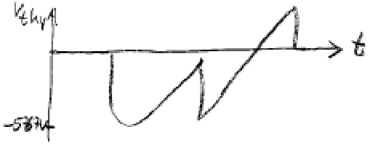
$\Rightarrow \quad \underline{C > 27 \mu F}$

7a) $V_d = \underline{360V}$

$\alpha = \underline{48°}$

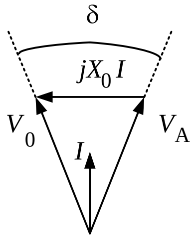
$T = \underline{3Nm}$





b) $\Delta V_d = \frac{6 L I_d}{T} \Rightarrow \underline{\alpha = 46,9°}$

8. a)



b) For short circuit in node A, the reactive power consumed by the internal impedance is given by

$$Q_k = 3V_{0phase} I_{sc} = 3V_{0phase}\frac{V_{0phase}}{X_0} = \frac{V_{0l-l}^2}{X_0} \Leftrightarrow X_0 = \frac{V_{0l-l}^2}{Q_k} = \frac{66000^2}{100 \cdot 10^6} = 43,56\ \Omega$$

When operating according to the formulation of the problem

$$P_A = \frac{3V_{0phase}U_{Aphase}}{X_0}\sin(\delta) \Leftrightarrow \sin(\delta) = \frac{P_A \cdot X_0}{3V_{0phase}U_{Aphase}} = \frac{30 \cdot 10^6 \cdot 43,56}{66000^2} = 0,300$$

$$\delta = 17,458°$$

$$\frac{1}{2}X_0 I = V_{0phase}\sin(\delta/2) \Rightarrow I = \frac{2 \cdot V_{0phase}}{X_0}\sin(\delta/2) = \frac{2 \cdot 66000}{\sqrt{3} \cdot 43,56}\sin(8,73°) = \underline{265,5\text{ A}}$$

c) The output current from the inverter is purely capacitive, i.e. the output current can be represented by a capacitance in parallel with the resistive load. The sum of the currents must equal the value found in b).

$$P = 3V_{Aphase} I_R \Leftrightarrow I_R = \frac{P}{3V_{Aphase}} = \frac{30 \cdot 10^6}{\sqrt{3} \cdot 66000} = 262,4\text{ A}$$

At the 66 kV-side the inverter current becomes

$$I_{v66} = \sqrt{I^2 - I_R^2} = \sqrt{265,5^2 - 262,4^2} = 40,3\text{ A}$$

and on the 16,5 kV-side the current is $I_{v16,5} = 161,2\text{ A}$.

The voltage across the reactor is given by $V_{react} = 161,2 \cdot 20 = 3224\text{ V}$.

The ouput voltage from the inverter must therefore be

$$V_{invphase} = \frac{66000}{\sqrt{3} \cdot 4} + 3224 = 12750\text{ V}.$$

$$V_{invphase} = m_a \frac{V_d}{2 \cdot \sqrt{2}} \Leftrightarrow m_a = \frac{2 \cdot \sqrt{2} \cdot V_{invphase}}{V_d} = \frac{2 \cdot \sqrt{2} \cdot 12750}{40000} = \underline{0,902}$$