University of Strathclyde

Department of Electronic and Electrical Engineering

EE466 Coursework

Assessment

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Glasgow, 2017

1. Q1

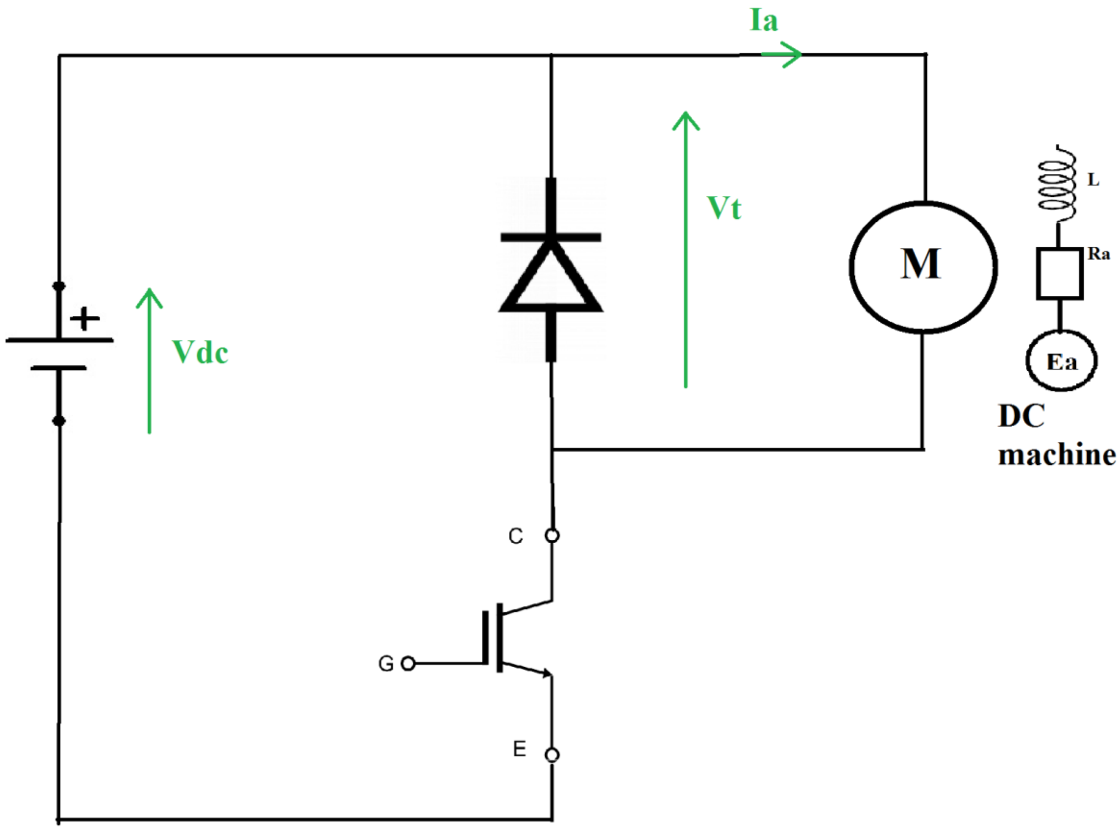


Fig. 1. DC chopper (separately excited DC machine is assumed).

Base speed - ω_{m1} =2000 rpm

Rated armature voltage - ε_{a1} = 500 V

Torque - T_{ind1}= T_{ind2} = T_{ind}= 40 Nm

Actual speed - ω_{m2} =2000 rpm = 209.43951 rad/s

General equation for DC machine:

$$\varepsilon_a = k_1\theta\omega_m \qquad \text{Back EMF} \qquad (1.1)$$

$$T_{ind} = k_1\theta I_a, \qquad \text{Torque} \qquad (1.2)$$

a) The current drawn by the machine's armature.

Using equation 1.1:

$$\frac{\varepsilon_{a1}}{\omega_{m1}} = \frac{\varepsilon_{a2}}{\omega_{m2}} \qquad (1.3)$$

$$\varepsilon_{a2} = \frac{\varepsilon_{a1}\omega_{m2}}{\omega_{m1}} = \frac{500*1500}{2000} = 375\ V \qquad (1.4)$$

Using equation 1.2 and 1.1 it is possible to calculate the current drawn by the machine needed to maintain the rated Torque.

$$\mathbf{I}_a = \frac{T_{ind}}{k_1\theta} = \frac{T_{ind\omega_{m1}}}{\varepsilon_{a1}} = \frac{40*209.43951}{500} = \mathbf{16.7552\ A} \quad \text{,Current drawn by machine} \quad (1.5)$$

b) Duty factor at which IGBT is turned on

The voltage across the DC machine V_t is described by the equation 1.6:

$$V_t = \underbrace{\cancel{I_a R_a}}_{\text{Assumption 2}} + \underbrace{\cancel{L\frac{dI_a}{dt}}}_{\text{Assumption 3}} + \varepsilon_a \quad \text{Voltage across DC machine} \quad (1.6)$$

Assumption 1: Resistance R_a in the DC machine is present and it limits the current I_a to desired value of 16.7552 A.

Assumption 2: There is no voltage drop on resistor R_a, if it is not the case $V_t > \varepsilon_a$.

Assumption 3: The ripple of I_a is infinitely small, meaning that I_a is constant (or having in mind that voltage drop across inductor equals to zero in steady state, but that would be average voltage)

Assumption 4: Voltage drops on IGBT and Diode are <u>not</u> considered when calculated the duty cycle. (In reality duty cycle should be slightly increased to make up for that)

$$\mathrm{d} = \frac{V_t}{V_{DC}} = \frac{\varepsilon_{a2}}{V_{DC}} = \frac{375}{500} = 0.75 \quad \text{,duty cycle} \quad (1.7)$$

c) The conduction losses in IGBT

At first, calculating the voltage drop across the transistor:

$$V_{CE} = V_{dropIGBT} + I_a R_{onIGBT} \quad (1.7)$$

$$V_{CE} = 1.9 + 16.7552 * 0.01 = 2.0676\ V \quad (1.8)$$

$$\boldsymbol{P_{condIGBT} = dV_{CE}I_a = 0.75 * 2.0676 * 16.7552 = 25.9823\ W} \quad \mathbf{(1.9)}$$

d) The switching losses in the IGBT

Firstly, one has to scale the ON and OFF energy for operating current and voltage:

$$E_{on} = E_{onRated}\frac{V_{used}}{V_{rated}}\frac{I_{used}}{I_{rated}} = 3 * \frac{500}{600}\frac{16.7552}{10} = 4.1888\ mJ \quad (1.10)$$

$$E_{off} = E_{offRated}\frac{V_{used}}{V_{rated}}\frac{I_{used}}{I_{rated}} = 2 * \frac{500}{600}\frac{16.7552}{10} = 2.7925\ mJ \quad (1.11)$$

$$\boldsymbol{P_{switchIGBt} = f_{sw}(E_{on} + E_{off}) = 5000 * (4.1888 + 2.7925) * 10^{-3} = 34.9065} \quad \mathbf{(1.12)}$$

e) The conduction losses in Diode

At first, calculating the voltage drop across the transistor:

$$V_D = V_{dropDiode} + I_a R_{onDiode} \quad (1.13)$$

$$V_D = 1.3 + 16.7552 * 0.014 = 1.5346\ V \quad (1.14)$$

$$\boldsymbol{P_{condDiode} = (1-d)V_D I_a = (1-0.75) * 1.5346 * 16.7552 = 6.4281\ W} \quad (1.15)$$

Heat sink rating:

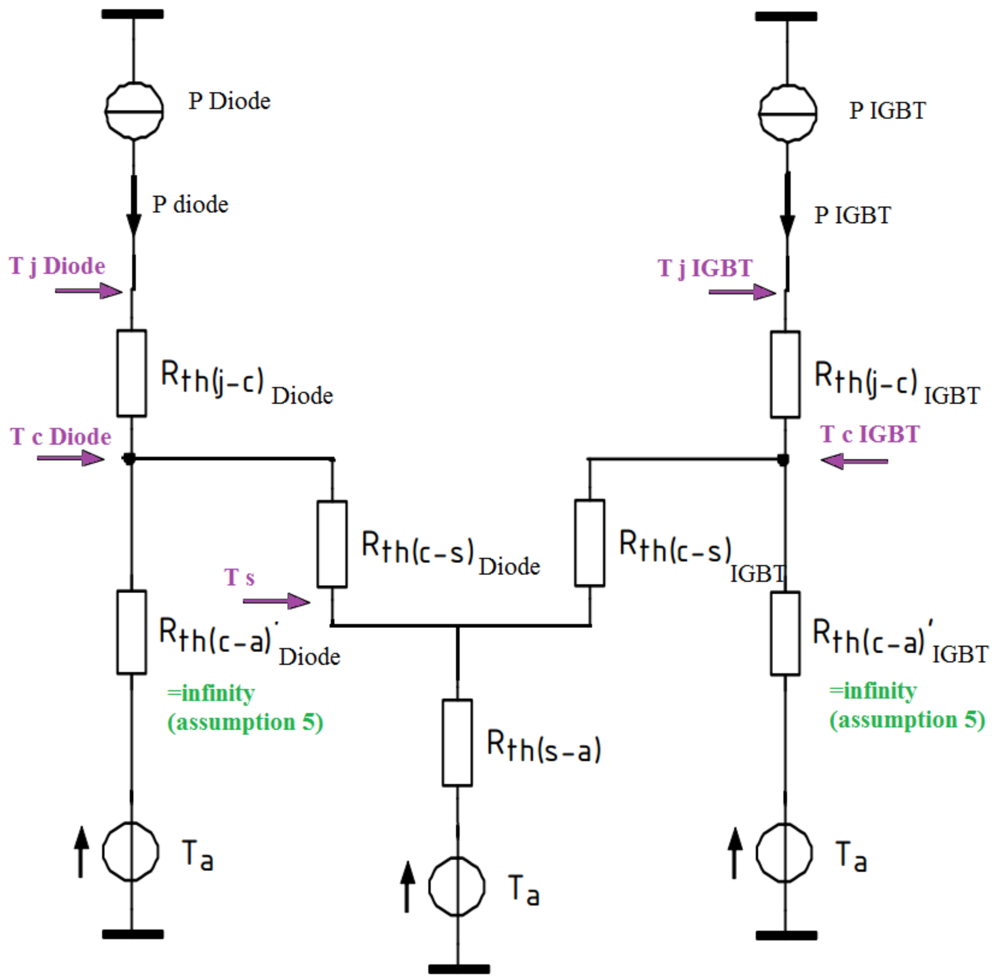


Fig. 2. Thermal circuit of the system.

Thermal	Electrical
Power	Current source
Thermal resistance	Resistance
Temperature difference	Voltage source
T= 0 K	Ground

Table. 1. System description.

Letter	*Meaning*
j	*Junction*
c	*Case*
s	*Heat sink*
a	*ambient*

Table. 2. Abbreviation meaning.

Note 1: $R_{th(c-a)'}$ – Increased resistance between c and a due to reduced surface when heat sink is applied

Assumption 5: $\mathbf{R_{th(c-a)'Diode}}$ **and** $\mathbf{R_{th(c-a)'IGBT}}$ are infinite.

Assumption 6: Continuous operation (no C or τ are provided). It is safer, because if a repetitive operation is assumed, the temperature could drop e.g. junction temperature when a device is OFF. P_{Diode} and P_{IGBT} are constant.

$P_{diode} = P_{condDiode} = 6.4281$ W

$P_{IGBT} = P_{condIGBT} + P_{switchIGBT} = 25.9823 + 34.9065 = 60.8888$ W

Calculating the temperature of the sink:

$$T_{jDiode} - T_{s1} = P_{Diode}(R_{th(j-c)Diode} + R_{th(c-s)Diode}) \tag{1.16}$$

$$T_{jIGBT} - T_{s2} = P_{IGBT}(R_{th(j-c)IGBT} + R_{th(c-s)IGBT}) \tag{1.17}$$

$$T_{s1} = T_{jDiode} - P_{Diode}(R_{th(j-c)Diode} + R_{th(c-s)Diode}) \tag{1.18}$$

$$T_{s2} = T_{jIGBT} - P_{IGBT}(R_{th(j-c)IGBT} + R_{th(c-s)IGBT}) \tag{1.19}$$

$$T_{s1} = 125 - 6.4281 * (0.5 + 1) = 115.3579\ °\text{C} \tag{1.20}$$

$$T_{s2} = 125 - 60.8888 * (0.2 + 0.7) = 70.2001°\text{C} \tag{1.21}$$

T_s is the sink temperature at which the device is working at safe temperature (125 °C). A lower value should be chosen to assure safer operation of the entire system (It means that diode junction will not exceed even lower temperature).

$$T_s - T_a = (P_{Diode} + P_{IGBT})R_{th(s-a)} \tag{1.22}$$

$$R_{th(s-a)} = (T_s - T_a)/(P_{Diode} + P_{IGBT}) \tag{1.23}$$

$$\boldsymbol{R_{th(s-a)} = \frac{70.2001-45}{6.4281+60.8888} = 0.3744\ °\text{C/K}} \tag{1.24}$$

Higher switching frequency	
Advantages	Disadvantages
Smaller volume/weight of passive components (inductor), having the same ripple current.	Switching losses staring to have even more contribution to overall Power dissipation.
Transient response can improve	Together with available smaller volume design, power dissipation density is becoming greater (additional volume of cooling system)
	EMI noise spectrum amplitude gets higher
	Reliability of the switches decreases.

Table. 3. Higher switching frequency.

Lower switching frequency	
Advantages	Disadvantages
Switching losses staring to have less contribution to overall Power dissipation.	Bigger volume/weight of passive components (inductor), having the same ripple current.
Together with available bigger volume design, power dissipation density is lower.	Transient response can worsen.
EMI noise spectrum amplitude gets smaller	
Reliability of the switches increases.	

Table. 4. Lower switching frequency.

2. Q2

a) Full bridge converter.

Average voltage can be calculated using following equation **[1]**:

$$U_{\mathrm{o(0)}} = u_{\mathrm{o(av)}} = \frac{1}{T_{\mathrm{s}}}\int_{T_{\mathrm{s}}} u_{\mathrm{o}}\mathrm{d}t = \frac{1}{T_{\mathrm{s}}}\int_{t_0}^{t_2} u_{\mathrm{o}}\mathrm{d}t = \frac{1}{T_{\mathrm{s}}}\left(\int_{t_0}^{t_1} u_{\mathrm{o}}\mathrm{d}t + \int_{t_1}^{t_2} u_{\mathrm{o}}\mathrm{d}t\right) = \frac{1}{T_{\mathrm{s}}}\left(\int_{t_0}^{t_1} U_{\mathrm{i}}\mathrm{d}t + \int_{t_1}^{t_2} (-U_{\mathrm{i}})\mathrm{d}t\right) =$$

$$= \frac{1}{T_{\mathrm{s}}}\left(U_{\mathrm{i}}\int_{t_0}^{t_1}\mathrm{d}t - U_{\mathrm{i}}\int_{t_1}^{t_2}\mathrm{d}t\right) = \frac{1}{T_{\mathrm{s}}}U_{\mathrm{i}}\left[(t_1 - t_0) - (t_2 - t_1)\right] = \frac{1}{T_{\mathrm{s}}}U_{\mathrm{i}}\left[DT_{\mathrm{s}} - (1-D)T_{\mathrm{s}}\right] =$$

$$= \frac{1}{T_{\mathrm{s}}}U_{\mathrm{i}}(2D-1)T_{\mathrm{s}} = (2D-1)U_{\mathrm{i}}$$

$$U_{o(0)} = (2D - 1)V_{dc} = (2 * 0.7 - 1) * 400 = 160\ V \tag{2.1}$$

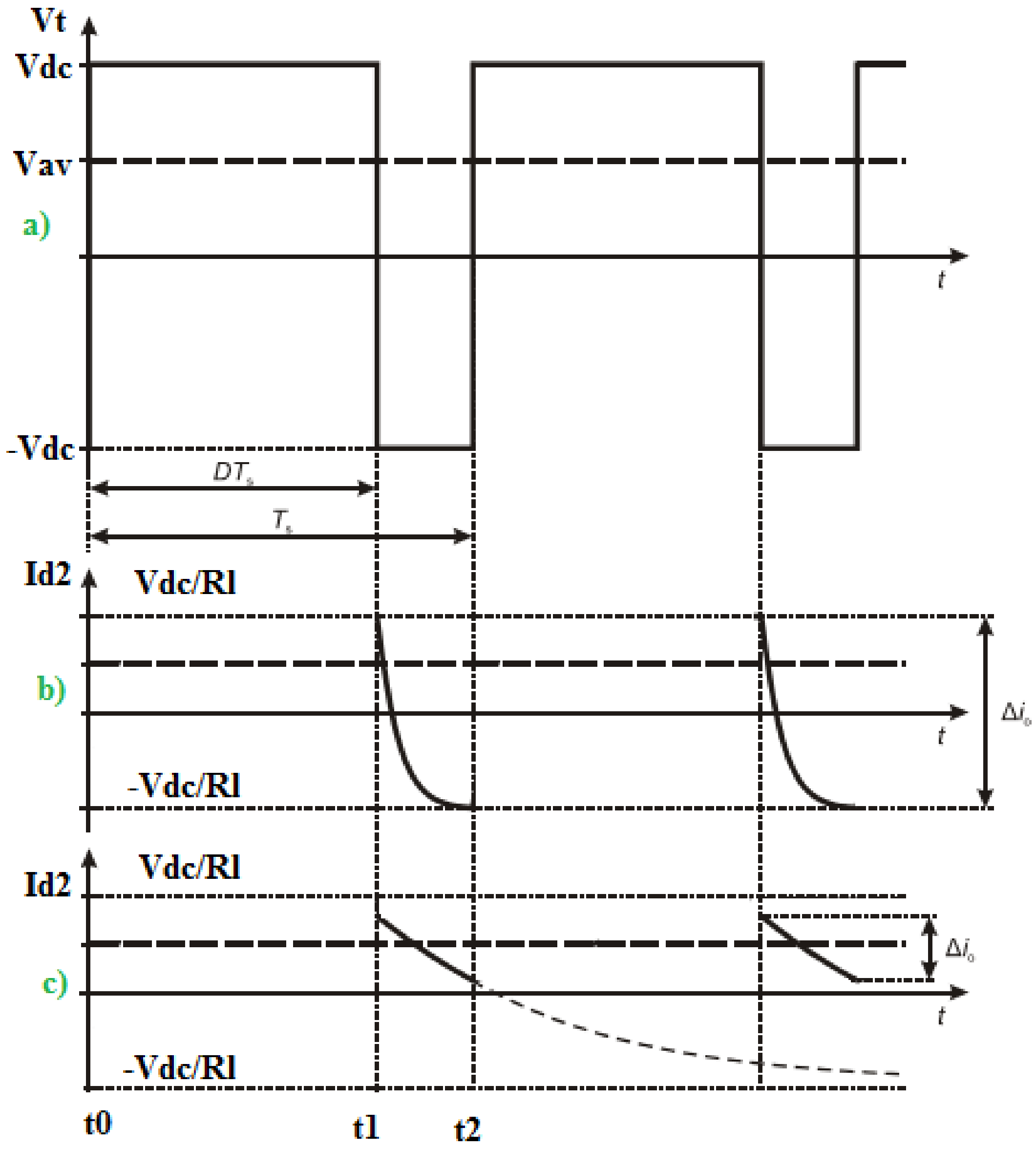


Fig. 3. Characteristics of full bridge rectifier. a) output voltage; b) Current on diode 2 with low inductance L1; c) Current on diode 2 with high inductance L1. (Adapted from ***[1]****)*

Negative off-state gate-emitter voltage

Current tailing effect during the turn OFF switching transient caused by stored minority carriers appears in IGBT transistors. "The tail current of IGBTs are caused by stored excess carriers in the wide and lightly doped N-base layer during its forward conduction. The width of this layer determines the voltage blocking ability of the device; however this layer adds significant resistance during forward conduction that results in stored excess carriers. These carriers produce a collector tail current during its turn OFF transient that limits the switching speeds of the device” **[2]**

Current injection Technique (CIT) or Non-Invasive Current Injection Technique (NICIT) may be applied to mitigate the IGBT’s current tail effect, both consist of applying negative off-state gate-emitter voltage.

b) Boost converter

$$i = \frac{1}{L}\int_0^t V dt + i_0 \text{ , Current across the inductor} \tag{2.1}$$

$$i = \frac{Vt}{L} + i_0 \quad \text{, for a constant rectangular pulse} \tag{2.2}$$

$$\Delta i_{on} = \frac{(V_{in} - V_{DropTR1})T_{on}}{L} \text{ , for transistor on} \tag{2.3}$$

$$\Delta i_{off} = \frac{(V_{out} - V_{in} + V_{DropD1})T_{off}}{L} \text{ , for transistor off} \tag{2.4}$$

$$\Delta i_{on} = \Delta i_{off} = \frac{(V_{in} - V_{DropTR1})T_{on}}{L} = \frac{(V_{out} - V_{in} + V_{DropD1})T_{off}}{L} \text{ , equating the volt-balance} \tag{2.5}$$

$$V_{out} = \frac{V_{in} - V_{DropTR1}\delta}{(1-D)} - V_{DropD1} \tag{2.6}$$

$$V_{out} = \frac{V_{in}}{(1-\delta)} \rightarrow \frac{V_{out}}{V_{in}} = \frac{1}{(1-\delta)} \tag{2.7}$$

Boost converter, usually step-up the voltage, but step down the current by factor **1/(D-1)**, thus higher voltage does not explain the need for higher capacitance on the output. The Capacitor will charge faster due to higher voltage, but also charge slower due to smaller current.

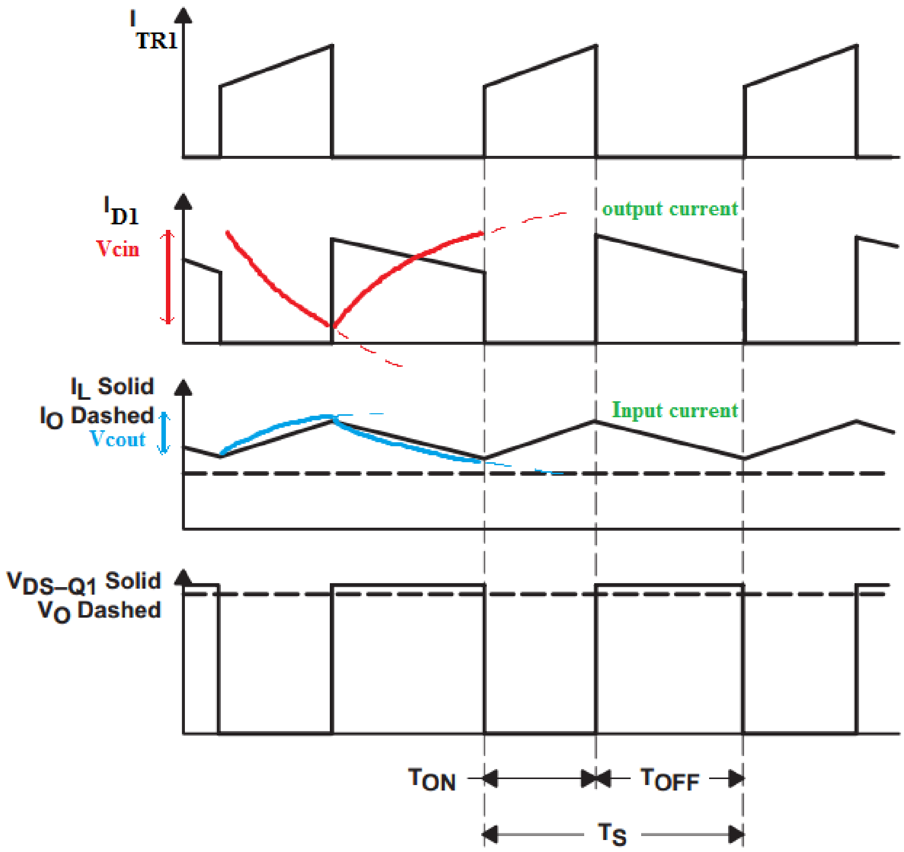


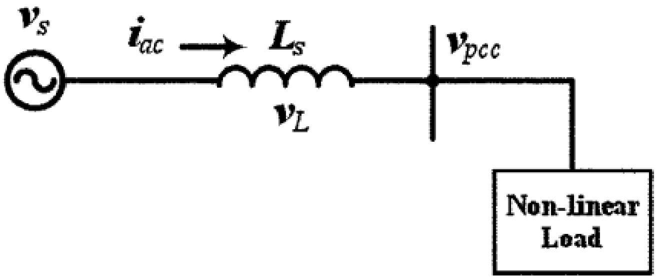
Fig. 4. Characteristics of boost converter (Adapted from ***[8]****)*

The difference is that the input current is continuous throughout the switching cycle, but output current will drop to zero when the switch TR1 is turned on. It means that voltage charging and discharging curves will have higher amplitude for the output capacitor. It means that in real application the capacitor should have also higher value.

c) Distortion

Non-linear load draws non-sinusoidal current, even when connected to a sinusoidal voltage source. Examples of such a load : Variable speed drives, Uninterruptible power supplies (UPS) Industrial rectifiers, Welding machines, Fluorescent lighting systems (electronic ballast) Computers Printers, Servers Electronic appliance **[3]**

The nonlinear current will cause distortion of the voltage in the Point of Common Coupling (PCC) due to high harmonic content. The shape of the V_{PCC} voltage depends on the line impedance and the shape of the i_{ac} (its harmonic content) **[6].**



$$v_{PCC} = (v_S - v_L) = \left\{ v_s - L_s \frac{d(i_{ac})}{dt} \right\}$$

Fig. 5. Non-linear load supplied by Vs source ***[6].***

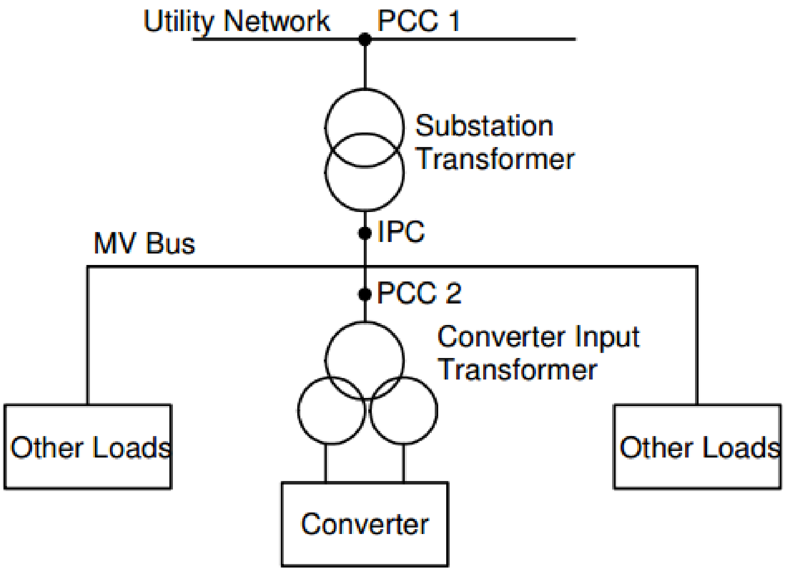


Fig. 6. Non-linear converter grid connection ***[3]****.*

The distortion may be caused by other load than the devices used in the office building. This phenomena should be mitigated in order to comply the standards e.g. IEC 61000-2-4, Rev. 2002 (worldwide).

c) Thyristor control

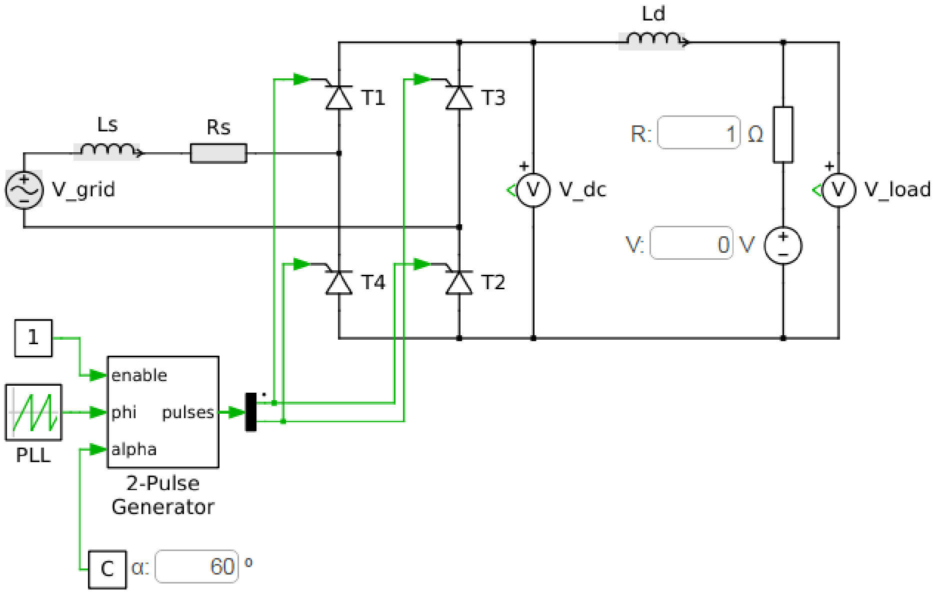


*Fig. 7. Thyristor rectifier **[4]**.*

The rectifier consists of four thyristors T1 , T2 , T3 and T4 connected in the form of full wave bridge configuration. Each pair of thyristors (T1 + T2 and T2+T4) are switched on, on turns. Pair T1 + T2, are turned on from 0 + a to π (sin>0), and T2+T4 (sin<0) from π + a to 2 π. Each thyristor has its own control circuitry and switches off, whenever the voltage across it’s terminal is equals to zero. It may be the case that the thyristors are switched off later when the load is inductive, because the choke will maintain the current across the thyristor not allowing to switch off the thyristor.

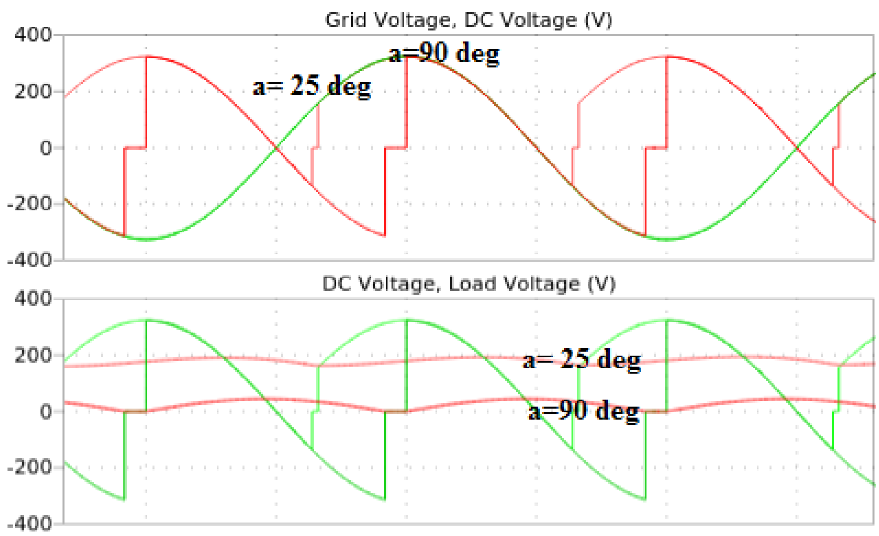


Fig. 8. Thyristor rectifier, output voltage, firing angle dependence [4].

The firing angle a will determine the voltage output, the higher the a, the smaller output voltage will be.

$$V_{dc} = \int_{a}^{\pi} V_m \sin(\omega t)\, dt \tag{2.8}$$

$$V_{dc} = \frac{V_m}{\pi}(1 + \cos(a)) \tag{2.9}$$

Attributes:

- Relatively simple control (comparing to VSC topologies)

- low switching frequency

- High efficiency (LCC topology 0.7 % compared to 1.2 % loss for VSC according to **[5]**)

Disadvantages:

- LCC cannot be used for separate compensation and grid support.

- Drawing non-sinusoidal current (harmonic currents).

- Limited reactive power control (e.g. in HVDC application).

e) Presence of harmonic currents

Problems:

- Generator additional heating due to increased iron losses, and copper losses because they are frequency dependent and increase with increased harmonics.
- Transformer additional heating due to increased iron losses (eddy's currents, hysteresis) and copper losses because both are frequency dependent and increase with increased harmonics.
- Induction motor additional heating due to increased iron losses, and copper losses.
- Higher transmission losses, due to amplified skin effect
- More frequent protection false tripping
- Additional EMI noise.
- Distortion of the utility voltage (as discussed in the question 2 c)

Problem mitigation:

- generators supplying nonlinear loads are required to be derated
- Setting the distribution transformers in Delta-Delta and Delta-Wye configuration.
- Use of reactor
- Passive Harmonic Filters
- Active filters (based on Voltage Link Back-to-Back connected Converter)
- "Active front ends" (AFE), also known as "sinusoidal input rectifiers" **[6]**.

f) Heat sink

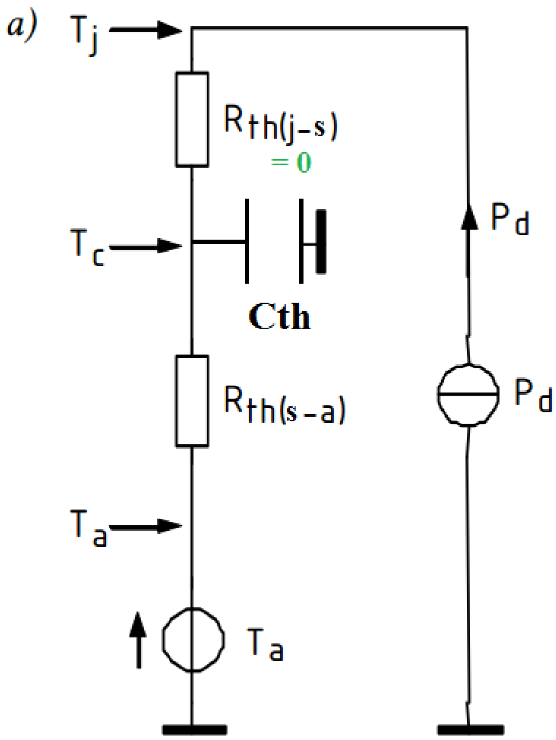


Fig. 1. Thermal circuit of the system.

Using equations, 2.10 and 2.11 it is possible to calculate the Temperature above ambient.

$$T_j = P_d Z_{th} + T_a \qquad , Z_{th} = R_{th(s-a)}(1 - e^{\frac{-t}{R_{th(s-a)}C_{th}}}) \tag{2.10;2.11}$$

$$T_j = 12 * 1.18 + T_a \quad , Z_{th} = 12 * \left(1 - e^{\frac{-7*60}{4*300}}\right) = 1.18 \tag{2.12;2.13}$$

$$\boldsymbol{T_j = 14.16\ K + T_a} \tag{2.14}$$

References:

[1] Ł. Starzak, „Przetwornica mostkowa Sterowanie silnikiem prądu stałego”, Lodz University of Technology, 2010.

[2] S. Eio and N. Shammas, "IGBT tail current reduction by current injection technique", 2008 43rd International Universities Power Engineering Conference, 2008.

[3] ABB, “Harmonic distortions & solutions,” 2010.

[4] "Single-Phase Thyristor Rectifier | Plexim", Plexim.com, 2017. [Online]. Available: https://www.plexim.com/academy/power-electronics/thyristor-rect-ind-load. [Accessed: 06-Apr- 2017].

[5] S. K. Merz, „Calculating Target Availability,” Newcastle upon Tyne, 21st December 2012.

[6] N. Shah, „Harmonics in power systems,” May 2013.

[7] Infineon, „Thermal equivalent circuit models,” 2008.

[8] Texas Instruments, “Understanding boost power stages in switchmode power supplies”, Application Report SLVA061, pp. 2-3.

Course work assessment

EE466/966

2016-17 session

Power electronics section

Introduction

The objective of this coursework exercise is to consolidate the lecture material that you have received to date.

Another important objective is to assist you in the development of transferable skills, such as report writing, presentation of technical material and examination technique.

The assessment

The assessment consists of **two** questions where the majority of the material has been covered to greater or lesser degrees during lectures. Answer **both** questions.

Submission

- You may submit either word processed or hand-written solutions.
- Your submission should be suitably bound and must include a cover sheet.
- When including your name on the coversheet, it must be presented in the order:

First Name Family Name

- If your solutions require graph paper, then it is your responsibility to provide this.
- Your solutions should resemble "specimen solutions" i.e. the type of solution that you may expect to see in a textbook. Solutions must be clearly presented legible and concise. You should show all your mathematical working. Diagrams and graphs must be clear and contain all the relevant information.

Your completed assessment must be submitted to the Resource Centre by 4pm on Friday 7 April.

Q1 A DC machine has the following parameters:

- Base speed: 2000rpm
- Rated armature voltage: 500V
- Rated torque: 40Nm

The machine operates as a motor and its armature is supplied from a DC chopper formed by an IGBT and a pn-diode. The input voltage to the chopper is 500V and it operates under pulse width modulation (PWM) control at a switching frequency of 5kHz.

Data for the IGBT are:

- V_{on} = 1.9V
- R_{on} = 10mΩ
- E_{on} = 3mJ when switching 600V and 10A
- E_{off} = 2mJ when switching 600V and 10A

Data for the diode are:

- V_{on} = 1.3V
- R_{on} = 14mΩ

If the machine is running at 1500rpm and at its rated torque, calculate the following quantities:

a) the current drawn by the machine's armature
b) the duty factor at which the IGBT is turned on for
c) the conduction losses in the IGBT
d) the switching losses in the IGBT
e) the conduction losses in the diode

The IGBT and the diode are mounted onto a heatsink. (One heatsink is used to hold both devices.) Thermal resistances are as follows:

- Diode junction to case: 0.5°C/W
- Diode case to heatsink: 1.0°C/W
- IGBT junction to case: 0.2°C/W
- IGBT case to heatsink: 0.7°C/W

Reliability data has shown that the maximum safe junction temperature for both the diode and the IGBT is 125°C. If the worst-case ambient temperature to be encountered is 45°C, calculate the heatsink rating (thermal resistance) required. Sketch a thermal circuit for the system to explain your answer.

With respect to the expected effects on both the chopper and the machine, discuss the advantages and disadvantages of using:

- a higher switching frequency;
- a lower switching frequency.

[100%]

Q2 Q2a The full-bridge circuit in Figure Q2a operates under pulse width modulation (PWM) control. TR1 and TR4 are switched on simultaneously at a duty factor of 70%. TR2 and TR3 are held off throughout the switching cycle. V_{in} is 400V. Calculate the average voltage appearing across the load resistance, R_L. Sketch the current waveform appearing in D2. According to the manufacturer's data sheet, applying a voltage of 0V between the gate and emitter of the IGBT type used in locations TR1-4 will result in it being fully turned off. However, it may be necessary to apply a negative off-state gate-emitter voltage when the IGBT is deployed in the circuit in Figure Q2a. Explain why this is the case.

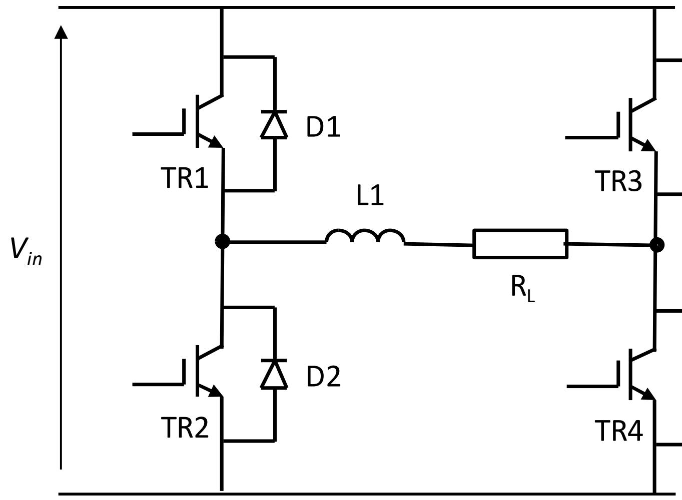


Figure Q2a: Full-bridge power converter

[20%]

Q2b Figure Q2b shows a boost converter. It operates under pulse width modulation (PWM) control and in the continuous conduction mode (CCM). By equating the voltage appearing across the choke (L1) during the transistor's on-time and that during its off-time, show that the voltage gain, $\frac{V_{out}}{V_{in}}$, is given by $\frac{V_{out}}{V_{in}} = \frac{1}{1-\delta}$ where δ is the duty factor at which TR1 is driven on. Explain why the output capacitance, C2, is likely to be greater than the input capacitance, C1, in a practical application.

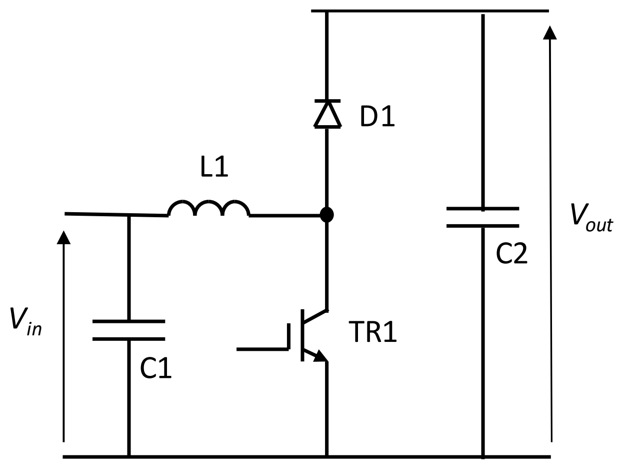


Figure Q2b: Boost converter

[20%]

Question continues

Q2c The left-hand waveform in Figure Q2(c) shows an ideal AC mains sine wave voltage. The right-hand waveform show the mains voltage observed at the wall socket in an office building. Explain why it might exhibit the distortion evident when observed in this particular environment.

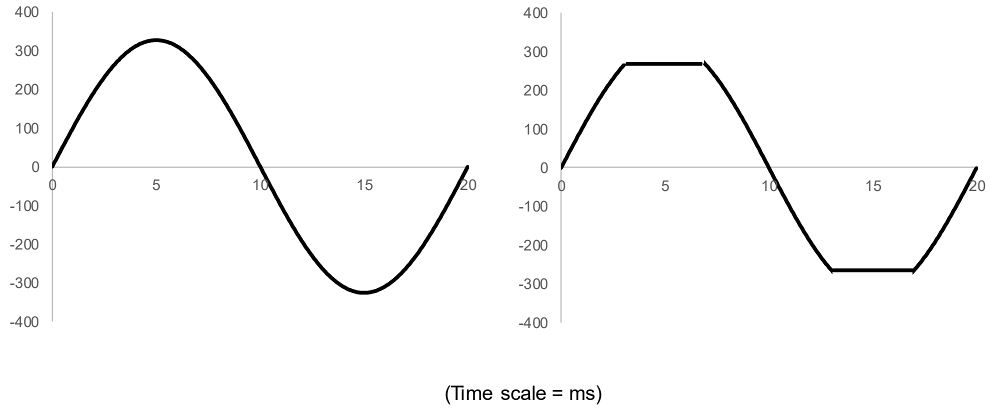


Figure Q2c: Ideal (left) and distorted (right) supply voltages

[15%]

Q2d Sketch a thyristor rectifier circuit that is supplied from the left-hand waveform in Figure Q2c and used to vary the voltage applied to a load. Explain how it works and discuss its attributes and drawbacks.

[15%]

Q2e Discuss the problems that might arise in a power system due to the presence of harmonic currents, and how these currents might be minimised.

[15%]

Q2f A power semiconductor device is mounted onto a heatsink with a thermal resistance to ambient of 4°C/W and a thermal capacitance of 300J/°C. The thermal resistances between the transistor junction and the heatsink are taken as being negligible here. The device dissipates 12W when it is operating. Calculate the temperature above ambient of the device's junction at seven minutes after energisation from cold.

[15%]