

CALCULATION SHEET

Sheet: 7 of 7

TITLE: Power Electronics

SITE:

DATE:

REV.

DONE BY

APPR.

DESCRIPTION:

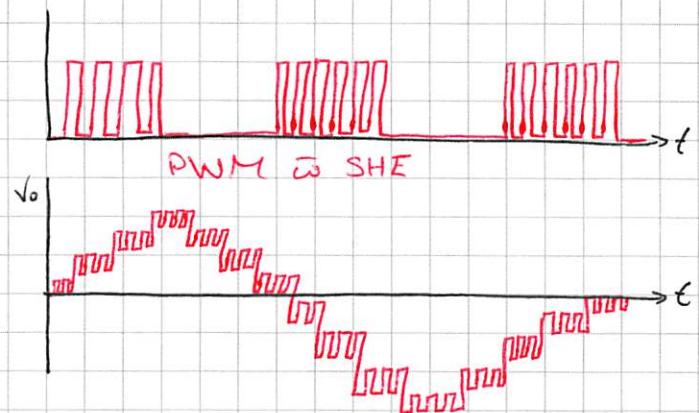
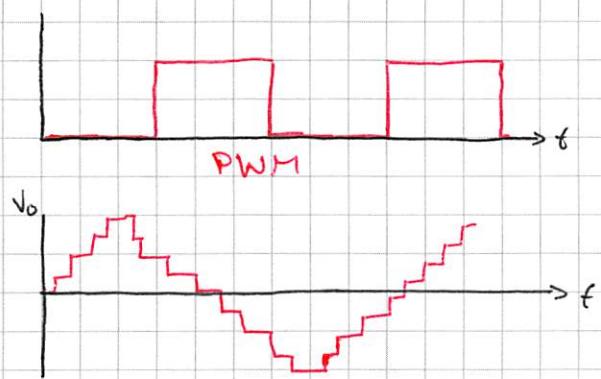
Theoretical

PROJECT ID:

REFERENCE(S):

Explain Selective Harmonic Elimination with Graphs. (SHE)

- Selective Harmonic Elimination (SHE) introduces additional notches in the basic voltage waveform of the square-wave inverter.
- The output voltage is "chopped" a number of times at an angle to eliminate Selected harmonic components



Functional Considerations for 3Ø Inverters

- Need good snubber circuits to reduce voltage spikes between switching
- The switching element activation should ensure 120° phase separation between outputs
- Must keep quarter-wave symmetry
- Switching Time
- Provide Voltage & Frequency Control
- Must use complementary branch switching as to not short circuit the supply
 - ↳ Blanking time
- Filtering
- Modulation Technique to eliminate harmonics & improve fundamental

List 3 different methods for eliminating or reducing output harmonics in inverters.

- Low Pass Filter on output
- Selective Harmonic Elimination
- Multiple PWM
- Harmonic Injection PWM
- Non-Sinusoidal Modulation
- Staircase PWM
- Trapezoidal PWM
- Random PWM
- Space Vector Modulation
- Hysteresis-band Current Control (HBCC)

Considerations for selecting m_f

- Always has to be an odd integer to create blanking time
- Higher values of m_f result in higher/increased switching losses
- Higher values of m_f also result in lower efficiency.

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What is the major challenge for operating an inverter?

- Whenever the voltage $v_o(t)$ and current $i_o(t)$ are not the same polarity, then $i_o(t)$ flows through the anti-parallel diodes, otherwise, it flows through the switching elements
- Limited Fundamental Component at the output
- Harmonics
- THD must meet grid requirements, if being grid-connected
- Maintain periodic output to prevent DC in load, make sure to have quarter-wave symmetry

What is blanking time and why is it important?

- Blanking time is the delay between switching pulses (ON-OFF-ON)
- Important so two switching elements in the same leg are not on at the same time which could short the DC input supply.
- Finite switching time delay to ensure no short circuit across DC input

Briefly explain the basic concept of PWM technique for 10 inverters.

- Allows elimination of specific harmonic components
- Output voltage & current control
- Sine wave (reference) compared with Triangular/Sawtooth waveforms
- Can be half or full-bridge
- V_s has a pulse when $Q_1 \& Q_2$ or $Q_3 \& Q_4$ are activated, allowing i_o to flow
- Adjust δ width to remove harmonic, width of pulses has to be determined off line

Output filters in inverters suffer from a main functional limitation, what is this limitation?

- Low Pass filters designed for cutoff frequency (size of components will depend on switching freq, technique and # of phases)
- Cannot help the fundamental component/value (ie. can't boost the fundamental)
 - ↳ Eliminates harmonics for a better THD but...
 - ↳ Energy in the fundamental remains the same and the energy in the harmonics is lost

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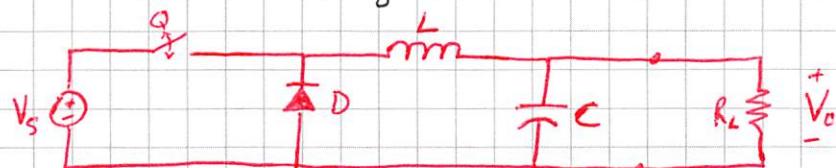
PROJECT ID:

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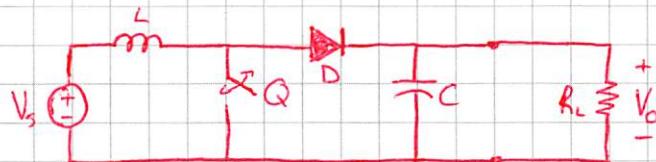
List 2 differences between the flyback and buck-boost DC-DC PECs.

- Flyback converters are isolated, where Buck-Boost converters are not.
- Flyback converters can supply multiple loads by using a multi-tap, high freq. transformer, where Buck-Boost PECs can only supply 1 load/branch
- Buck-Boost PECs can handle much higher powers than Flyback converters.

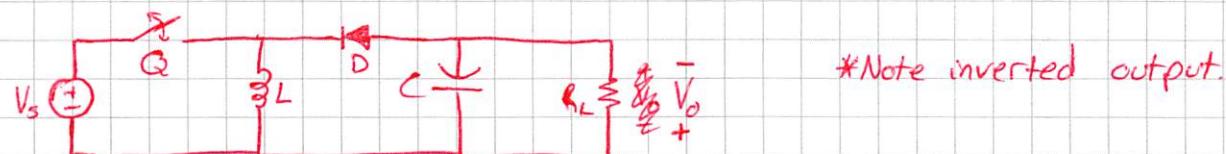
Draw the circuit Diagram for the Buck DC-DC PEC.



Draw the circuit Diagram for the Boost DC-DC PEC.



Draw the circuit Diagram for the Buck-Boost PEC.



What is the main concept of operating DC-AC converters?

- DC-AC converters have a main function of converting DC voltages/currents into 1Ø or 3Ø AC voltages & currents, along with providing voltage & frequency control with only one power stage. This function is achieved by operating inverter switching elements in a periodic sequential manner of either fully ON or fully OFF
- Periodic & Sequential Switching, with Complementary switching actions

List 3 different methods for eliminating or reducing the output harmonics in inverters

- Low pass filter on output
- Multiple pulse width Modulation
- SHE (Selective Harmonic Elimination) ~ multiple notches remove/eliminate harmonics
- Topology of the inverter

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<p>The analysis of DC switch mode converters makes assumptions of periodic steady-state operation of these converters, what are the implications of such assumptions?</p> <ul style="list-style-type: none"> - The average voltage across the inductor is zero - The average current through the capacitor is zero - These assumptions facilitate/allow for a simplified analysis - The assumptions also ignore the parasitics of capacitors, treating them as ideal elements, further allowing for simplified analysis. 						
<p>Why is it recommended to operate Buck Converters with high values of Duty Cycle ($D \rightarrow 1$)?</p> <ul style="list-style-type: none"> - In a Buck converter, higher output current, I_o, is desired, so we need a longer 'ON' time, and thus, higher inductor current $I_o \uparrow = V_o \downarrow$ Duty cycle is similar to the turns Ratio in a transformer - Continuous mode 						
<p>Why is it recommended to operate Boost converters with low values of duty cycle ($D \rightarrow 0$)?</p> <ul style="list-style-type: none"> - In a boost converter, less 'on' time results in more capacitor charging $\rightarrow V_o \uparrow$ - Converter becomes unstable/non-linear at higher Duty Cycles ($D > 0.8$) - Fairly linear relationship at low values of Duty Cycle - At duty cycles of 0.9999 (≈ 1), switch is always on, inductor saturates & becomes a current source, Diode is always reverse biased \rightarrow No current goes to the load, any voltage can be seen at output (random) but no current $I_o \approx 0$ 						
<p>Describe the function of a Buck-Boost Converter.</p> <p>A Buck-Boost converter can increase & decrease the output voltage</p> <ul style="list-style-type: none"> - $D > 0.5 \rightarrow$ Acts as a Boost converter & $V_o > V_s$ - $D < 0.5 \rightarrow$ Acts as a Buck converter & $V_o < V_s$ <p>This converter inverts the output voltage compared to Buck or Boost converters.</p>						
<p>The DC Flyback converter can be switched at higher frequencies than switch mode DC converters, what supports such a feature?</p> <ul style="list-style-type: none"> - The DC Flyback converter has a high frequency transformer which isolates the output from the input \rightarrow This also serves as protection from current spikes. 						

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When designing input filters for AC-DC converters, what are the main trade-offs in selecting the components?

- Capacitors & Inductors improve voltage & current signals, but higher current drawn from AC sources (More power losses, heat, & lower efficiency)
- Harmonic Distortion is a concern
- Reduced THD_I (L), but brings down PF, so a capacitor is needed which will end up changing the THD_I
- Must be aware of heating effects
- Make sure they don't affect switching

What are the main differences between designing input and output LC filters for 1Ø & 3Ø full-wave rectifiers?

- When designing the input filter, in a single phase system, we are concerned about cleaning the 3rd harmonic, requires a better & more expensive filter
- When designing the input filter, in a 3Ø system, we are concerned about cleaning the 5th harmonic, a less sophisticated filter is required.
- When Designing the output filter for:
 - 1Ø system - Concerned about cleaning 2nd harmonic (Difficult)
 - 3Ø system - Concerned about cleaning 6th harmonic (Easier)
- It is easier to filter the higher harmonics.

List 3 objectives for designing input and output filters for AC-DC power electronic converters.

- Must Reduce THD_I to be less than 5% (by standards)
- Input filters of a 3Ø PEC (AC-DC) must target the 5th harmonic, while the input filter of a 1Ø AC-DC PEC must target the 3rd harmonic
- Output filters of a 3Ø ACDC PEC must target the 6th harmonic, while the output filter of a 1Ø ACDC PEC must target the 2nd harmonic
- In the design stage, you are seeking to get the best power factor preferably PF > 70%

What is the main concept of DC switch mode converters?

- Switching must be sequential & periodic
- Connect & Disconnect a load to the supply on a periodic basis. The duration of each connect & disconnect have to be based on a certain level of control
- Output can be adjusted by varying the duty cycle
↳ PWM controlled
- Single Phase
- Regulated

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List 3 factors that can influence power losses (Switching & Conduction) in power electronic devices / switching elements.

- Switching Frequency
- Use of a Snubber Circuit
- Switching Times
- 'ON' voltage & current Ratings
- Leakage Current
- Duty Cycle (maybe)
- Device Characteristics

Inductive loads can impact the specifications for heat sinks, explain why.

- In cases of inductive loads, the switching losses are higher because the current being drawn takes a longer time to change due to the inductance
- Because switching losses are higher, the sink must be designed/specify to dissipate the extra heat from the additional Power Losses.

What is the main concept of AC Rectification?

- Sequential Switching
- Periodic Patterns
- Not allowing signals to swing below zero volts
- Making AC Signals DC Signals

The inductance behaves in steady-state as a short circuit to DC currents & voltages, why do inductive loads represent a major operational concern in an AC-DC Converter?

- Inductive loads can cause/force the diodes to conduct while reverse biased.
↳ This will fry the diodes or switching elements
- Can be fixed with a free-wheeling Diode
- Delays input current → can fry the component

What are the main differences between the diodes used in an AC-DC rectifier and the free-wheeling diodes?

- Free-wheeling diodes have shorter switching times than the normal AC-DC diodes
- Used to eliminate sudden changes in voltage & current
↳ Part of a snubber circuit
- Conduct when other diodes are reverse biased.

What are the main requirements for operating & controlling AC-DC Thyristor based converters?

- Phase-controlled thyristors must be capable of handling high voltages & currents with low conduction losses.
- Thyristors begin conducting when given a voltage signal/pulse from a controller & stop conducting when the voltage across them goes negative.

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<p>What are the main differences between current-controlled & voltage-controlled power electronic switching elements?</p> <ul style="list-style-type: none"> - Driver circuits are different - Current Driven devices require a good amount of base current to get going, this is the reason for slower switching times - Voltage-controlled requires a voltage signal to change operating states, versus a current-controlled which requires a current signal - Different switching times <ul style="list-style-type: none"> - Current Driven → Slower (ie. BJT) - Voltage Driven → Faster (ie. MOSFET, IGBT, Thyristor) 							
<p>Power Electronic Converters are described as sequentially operated switching elements. What are the requirements for maintaining such sequential switching activities?</p> <ul style="list-style-type: none"> - Switching from ON to OFF States and back on (OFF → ON) - Switching time is constant - The sequence/pattern of ON-OFF-ON-OFF is fixed - The switching can be used to convert voltage & current magnitudes, frequencies or polarities 							
<p>When designing a heat sink for a power electronic element, what needs to be considered?</p> <table border="0"> <tr> <td style="vertical-align: top;"> <ul style="list-style-type: none"> - Power Losses (conduction & switching) - Material of Device - Type of cooling (air, fan, gas, liquid) - Environment of Implementation - Thermal resistance of sink </td> <td style="vertical-align: top;"> <ul style="list-style-type: none"> - Size Constraints - Maximum Voltage & Current - Ambient Temperature - Electrical Isolation </td> </tr> </table>						<ul style="list-style-type: none"> - Power Losses (conduction & switching) - Material of Device - Type of cooling (air, fan, gas, liquid) - Environment of Implementation - Thermal resistance of sink 	<ul style="list-style-type: none"> - Size Constraints - Maximum Voltage & Current - Ambient Temperature - Electrical Isolation
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<p>How can a snubber circuit provide limitations on voltage & current changes in power electronic switching elements?</p> <ul style="list-style-type: none"> - The use of an inductor in a snubber circuit will limit current changes, especially at high switching frequencies because it appears as high impedance <ul style="list-style-type: none"> ↳ Resists changes in current when energizing & de-energizing - The use of a capacitor in a snubber circuit limits the voltage changes due to the charging & discharging characteristics. <ul style="list-style-type: none"> ↳ Also decreases power losses. 							

ECE4643: Power Electronics

Assignment 4: Solution

Q1:

Q2

A 1ϕ half-bridge inverter is fed with $V_s = 48$ V(dc), to supply a resistive load of $R_L = 2.4 \Omega$ at 60 Hz. for this inverter determine:

- The rms value of the fundamental component of the output voltage.

The rms value of the fundamental component of the output voltage V_{O1} for a half-bridge inverter is determined as:

$$V_{O1} = \frac{2V_s}{\sqrt{2}\pi} = \frac{2 \times 48}{\sqrt{2}\pi} = 21.6 \text{ V}$$

- The output power,

The output power P_O can be determined as:

$$P_O = \frac{V_{O1}^2}{R_L} = \frac{21.6^2}{2.4} = 194.4 \text{ W}$$

- The output current peak and rms values.

The output peak current can be calculated as:

$$(i_O)_{Peak} = \sqrt{2} \times \frac{V_O}{R_L} = \sqrt{2} \times \frac{48/2}{2.4} = 14.14 \text{ A}$$

The rms value of the output current I_O is determined as:

$$I_O = \frac{V_O}{R_L} = \frac{48/2}{2.4} = 10 \quad A$$

d) The value of THD_V .

$$\text{THD}_V = \frac{\left(\sum_{n=1,3,\dots}^{\infty} V_{On}^2\right)^{\frac{1}{2}}}{V_{O1}}$$

where:

$$\left(\sum_{n=1,3,\dots}^{\infty} V_{On}^2 \right)^{\frac{1}{2}} = (V_O^2 - V_{O1}^2)^{\frac{1}{2}} = \sqrt{24^2 - 21.6^2} = 10.46$$

The value of THD_V can be evaluated as:

$$\text{THD}_V = \frac{10.46}{21.6} = 48.43\%$$

Q3:

Repeat **Q2** for a full-bridge inverter.

a) The rms value of the fundamental component of the output voltage.

The rms value of the fundamental component of the output voltage V_{O1} for a full-bridge inverter is determined as:

$$V_{O1} = \frac{4V_s}{\sqrt{2}\pi} = \frac{4 \times 48}{\sqrt{2}\pi} = 43.2 \quad V$$

b) The output power,

The output power P_O can be determined as:

$$P_O = \frac{V_{O1}^2}{R_L} = \frac{43.2^2}{2.4} = 777.6 \quad W$$

c) The output current peak and rms values.

The output peak current can be calculated as:

$$(i_O)_{Peak} = \sqrt{2} \times \frac{V_O}{R_L} = \sqrt{2} \times \frac{48}{2.4} = 28.28 \text{ A}$$

The rms value of the output current I_O is determined as:

$$I_O = \frac{V_O}{R_L} = \frac{48}{2.4} = 20 \text{ A}$$

d) The value of THD_V .

$$THD_V = \frac{\left(\sum_{n=1,3,\dots}^{\infty} V_{On}^2\right)^{\frac{1}{2}}}{V_{O1}}$$

where:

$$\left(\sum_{n=1,3,\dots}^{\infty} V_{On}^2\right)^{\frac{1}{2}} = (V_O^2 - V_{O1}^2)^{\frac{1}{2}} = \sqrt{48^2 - 43.2^2} = 20.92$$

The value of THD_V can be evaluated as:

$$THD_V = \frac{20.92}{43.2} = 48.43\%$$

Q4

A 1ϕ full-bridge inverter is switched using the bipolar SPWM for $V_s = 300 \text{ V(dc)}$, $m_a = 0.8$, $m_f = 39$, and $f_o = 47 \text{ Hz}$. For this inverter, determine the rms value of the fundamental component of the output voltage, and the first 5 dominant harmonic components. The rms values of the harmonic components due the bipolar SPWM can be stated as:

$$(V_O)_n = \frac{V_s}{\sqrt{2}} \times (V_{On})_{p.u}$$

where $(V_{On})_{p.u}$ is the associated p.u value of the harmonic components as stated in the table of lecture 23. For $n = 1$ (the fundamental component):

$$(V_O)_1 = \frac{300}{\sqrt{2}} \times 0.8 \times 0.49 = 103.94 \times 0.8 = 83.16$$

As for the bipolar SPWM, the harmonic patches will be centered at multiples of $m_f \times f_m$. The first harmonic patch will be centered at $(m_f \pm 2) f_m$. In this inverter case, $m_f = 39$, and $m_a = 0.8$. Remember that n is the harmonic order.

for $n = m_f - 2 = 37$:

$$(V_O)_{37} = \frac{300}{\sqrt{2}} \times 0.135 = 212.13 \times 0.135 = 28.64$$

for $n = m_f + 2 = 41$:

$$(V_O)_{41} = \frac{300}{\sqrt{2}} \times 0.135 = 212.13 \times 0.135 = 28.64$$

There will be another harmonic patch centered at $(m_f \pm 4) f_m$, and using the table, these harmonic components will have a p.u value of 0.005 (negligible). The second patch of harmonics will be centered at $(2m_f \pm 1) f_m$.

for $n = 2m_f - 1 = 77$:

$$(V_O)_{77} = \frac{300}{\sqrt{2}} \times 0.192 = 212.13 \times 0.192 = 40.73$$

for $n = 2m_f + 1 = 79$:

$$(V_O)_{79} = \frac{300}{\sqrt{2}} \times 0.192 = 212.13 \times 0.192 = 40.73$$

There will another harmonic patch centered at $(m_f \pm 5) f_m$, and using the table, these harmonic components will have a p.u value of 0.008 (negligible).

Q5

Repeat **Q4** for the unipolar SPWM. The rms values of the harmonic components due the unipolar SPWM can be stated as:

$$(V_O)_n = \frac{V_s}{\sqrt{2}} \times (V_{On})_{p.u}$$

where $(V_{On})_{p.u}$ is the associated p.u value of the harmonic components as stated in the table of lecture 23. As for the unipolar SPWM, the harmonic patches will be centered at multiples of $2m_f \times f_m$. The first harmonic patch will be centered at $(2m_f \pm 1) f_m$. In this inverter case, $m_f = 39$, and $m_a = 0.8$. Remember that n is the harmonic order.

for $n = 1$ (the fundamental component):

$$(V_O)_1 = \frac{300}{\sqrt{2}} \times 0.8 \times 0.49 = 103.94 \times 0.8 = 83.16$$

for $n = 2m_f - 1 = 77$:

$$(V_O)_{75} = \frac{300}{\sqrt{2}} \times 0.192 = 212.13 \times 0.192 = 40.73$$

for $n = 2m_f + 1 = 79$:

$$(V_O)_{77} = \frac{300}{\sqrt{2}} \times 0.192 = 212.13 \times 0.192 = 40.73$$

There will be another harmonic patch centered at $(2m_f \pm 5) f_m$ with a p.u value of 0.008 (negligible). The second patch of harmonics will be centered at $(4m_f \pm 1) f_m$.

for $n = 4m_f - 1 = 155$:

$$(V_O)_{155} = \frac{300}{\sqrt{2}} \times 0.064 = 212.13 \times 0.064 = 13.58$$

for $n = 4m_f + 1 = 157$:

$$(V_O)_{157} = \frac{300}{\sqrt{2}} \times 0.064 = 212.13 \times 0.064 = 13.58$$

There will be harmonic patches centered at $(4m_f \pm 5) f_m$ with:

for $n = 4m_f - 5 = 151$:

$$(V_O)_{151} = \frac{300}{\sqrt{2}} \times 0.051 = 212.13 \times 0.051 = 10.82$$

for $n = 4m_f + 5 = 161$:

$$(V_O)_{161} = \frac{300}{\sqrt{2}} \times 0.051 = 212.13 \times 0.051 = 10.82$$

A third patch of harmonics is centered by $(4m_f \pm 7) f_m$ with a p.u value of 0.01 (negligible).

Notes for Q4 and Q5:

- For the bipolar SPWM, the dominant harmonics are located at $n = 37$, $n = 41$, $n = 77$, and $n = 79$.
- For the unipolar SPWM, the dominant harmonics are located at $n = 77$, $n = 79$, $n = 151$, $n = 155$, $n = 157$, and $n = 161$.
- Harmonic components, due to the unipolar and bipolar SPWM, may share magnitude values, however, they are located in different frequency bands.

ECE 4643: Power Electronics

Exam 2: Solution

Time: Wednesday, March 28th, 2018, 9:30-10:25 AM

Instructor: Dr. S. A. Saleh

Q1 [6 marks]

Q1.1-

Q1.2-

Q1.3-

Q2 [4 marks]

A DC buck-boost PEC has a supply voltage of $V_s = 24$, a duty cycle of $D = 0.4$, a switching frequency $f = 100 \text{ kHz}$, $L = 200 \mu\text{H}$, and $C = 80 \mu\text{F}$. If this PEC supplies a load of $R_L = 5 \Omega$. For this converter, determine:

- a) The output average voltage V_O .

In order to specify V_O , the mode of the dc PEC has to be determined. Using the boundary values of L_B and C_B , as:

$$L_B = \frac{(1-D)^2 R_L T}{2} = \frac{(1-0.4)^2 \times 5}{2 \times 100 \times 10^3} = 9.0 \mu\text{H}$$

$$C_B = \frac{DT}{2R_L} = \frac{0.4}{2 \times 100 \times 10^3 \times 5} = 0.4 \mu\text{F}$$

Since $L > L_B$ and $C > C_B$, then this dc PEC is operating in CCM. The output average voltage V_O can be determined as:

$$V_O = -V_s \left(\frac{D}{1-D} \right) = -24 \left(\frac{0.4}{1-0.4} \right) = -16 \text{ V}$$

- b) The inductor average current I_O .

The value of the average inductor current I_L is determined as:

$$I_L = \frac{DV_s}{R(1-D)^2} = \frac{24 \times 0.4}{5(1-0.4)^2} = 5.33 \text{ A}$$

- c) The maximum and minimum values of the inductor current.

The maximum (I_1) and minimum (I_2) inductor currents can be determined using the current

ripple in the inductor Δi_L , which is determined as:

$$\Delta i_L = \frac{DV_s}{fL} = \frac{0.4 \times 24}{100 \times 10^3 \times 200 \times 10^{-6}} = 0.48 \text{ A}$$

$$I_1 = I_L + \frac{\Delta i_L}{2} = 5.33 + \frac{0.48}{2} = 5.57 \text{ A}$$

$$I_2 = I_L - \frac{\Delta i_L}{2} = 5.33 - \frac{0.48}{2} = 5.09 \text{ A}$$

d) The output voltage ripple.

The ripple in the output voltage Δv_O can be determined as:

$$\Delta v_O = \frac{V_O D}{f R_L C} = \frac{16 \times 0.4}{5 \times 100 \times 10^3 \times 80 \times 10^{-6}} = 0.16 \text{ V}$$

Q3 [5 marks]

A flyback DC converter has to feed a resistive load ($R_L = 12 \Omega$) with $V_O = 12 \text{ V}$ from a supply of $V_s = 84 \text{ V}$. If this PEC has a high frequency transformer with $N_1/N_2 = 3$, and is operated at a switching frequency $f = 40 \text{ kHz}$, $L = 500 \mu\text{H}$, and $C = 200 \mu\text{F}$, determine:

a) The duty cycle D [1 mark]. The duty-cycle can be determined as:

$$\frac{V_O}{V_s} = \frac{D}{1-D} \left(\frac{N_2}{N_1} \right) \Rightarrow \frac{D}{1-D} = \frac{12}{84} \times 3 \Rightarrow D = 0.3$$

b) The inductor average current I_L [1 mark]. The average inductor current I_L can be determined using I_s as:

$$I_L = \frac{I_s}{D} = \frac{V_O^2 / (V_s R_L)}{D} = \frac{12^2 / (84 \times 12)}{0.3} = 0.4762 \text{ A}$$

c) The maximum and minimum values of the inductor current [1 mark]. The maximum (I_1) and minimum (I_2) inductor currents can be determined using the current ripple in the inductor Δi_L , which is determined as:

$$\Delta i_L = \frac{DV_s}{fL} = \frac{0.3 \times 84}{40 \times 10^3 \times 500 \times 10^{-6}} = 1.26 \text{ A}$$

$$I_2 = I_L + \frac{\Delta i_L}{2} = 0.4762 + \frac{1.26}{2} = 1.1062 \text{ A}$$

$$I_1 = I_L - \frac{\Delta i_L}{2} = 0.4762 - \frac{1.26}{2} = -0.1538 \rightarrow I_1 = 0 \text{ A}$$

Since $I_1 < 0$, the this PEC is operating on the boundary.

- d) The output voltage ripple [1 mark]. The ripple in the output voltage Δv_O can be determined as:

$$\Delta v_O = \frac{V_O D}{f R_L C} = \frac{12 \times 0.3}{12 \times 40 \times 10^3 \times 200 \times 10^{-6}} = 0.0375 \text{ V}$$

- e) The efficiency of this PEC [1 mark]. The efficiency can be determined as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_O I_O}{V_s I_s} = \frac{12 \times 0.4762}{84 \times 0.4762 \times 0.3} = 47.6\%$$

d) The output voltage ripple.

The ripple in the output voltage Δv_O can be determined as:

$$\Delta v_O = \frac{V_O D}{f R_L C} = \frac{16 \times 0.4}{5 \times 100 \times 10^3 \times 80 \times 10^{-6}} = 0.16 \text{ V}$$

Q3 [5 marks]

A flyback DC converter has a supply voltage of $V_s = 24$, $N_1/N_2 = 3$, a switching frequency $f = 40 \text{ kHz}$, $L = 500 \mu\text{H}$, and $C = 200 \mu\text{F}$. This converter supplies a load of $R_L = 5 \Omega$ at an average output voltage of $V_O = 5 \text{ V}$. For this converter, determine:

a) The duty cycle D .

The duty-cycle can be determined as:

$$\frac{V_O}{V_s} = \frac{D}{1 - D} \left(\frac{N_2}{N_1} \right) \Rightarrow \frac{D}{1 - D} = \frac{15}{24} \Rightarrow D = 0.385$$

b) The inductor average current I_L .

The average inductor current I_L can be determined using I_s as:

$$I_L = \frac{I_s}{D} = \frac{V_O^2 / (V_s R_L)}{D} = \frac{5^2 / (24 \times 5)}{0.385} = 0.542 \text{ A}$$

c) The maximum and minimum values of the inductor current.

The maximum (I_1) and minimum (I_2) inductor currents can be determined using the current ripple in the inductor Δi_L , which is determined as:

$$\Delta i_L = \frac{DV_s}{fL} = \frac{0.385 \times 24}{40 \times 10^3 \times 500 \times 10^{-6}} = 0.46 \text{ A}$$

$$I_1 = I_L + \frac{\Delta i_L}{2} = 0.542 + \frac{0.46}{2} = 0.772 \text{ A}$$

$$I_2 = I_L - \frac{\Delta i_L}{2} = 0.542 - \frac{0.46}{2} = 0.312 \text{ A}$$

d) The output voltage ripple.

The ripple in the output voltage Δv_O can be determined as:

$$\Delta v_O = \frac{V_O D}{f R_L C} = \frac{5 \times 0.385}{5 \times 40 \times 10^3 \times 200 \times 10^{-6}} = 0.048 \text{ V}$$

ECE4643: Power Electronics

Assignment 3: Solution

Q1:

- 1.
- 2.
- 3.
- 4.
- 5.

Q2

A DC Buck converter has an input voltage of 50 V, and an output voltage of 25 V at a switching frequency of 100 kHz. If the load is 125 W, determine:

- a) The duty cycle D .

The value of D can be determined using V_s and V_O as:

$$V_O = DV_s \implies D = \frac{V_O}{V_s} = \frac{25}{50} = 0.5$$

- b) The value of the ripple current in the inductor.

The value of the ripple current in the inductor Δi_L can be determined using the peak value of the inductor current $I_1 = 6.25$ A and the average value of the load current I_O as:

$$I_1 = I_O + \frac{\Delta i_L}{2} \implies \Delta i_L = 2(I_1 - I_O)$$

The average value of the load current I_O can be determined from V_O and the load power P_L as:

$$P_L = V_O I_O \implies I_O = \frac{P_L}{V_O} = \frac{125}{25} = 5 \text{ A}$$

The value of Δi_L can be obtained as:

$$\Delta i_L = 2(6.25 - 5) = 2.5 \text{ A}$$

c) The value of L to limit the peak inductor current to 6.25 A.

The value of the inductor L to limit the peak inductor current to 6.25 A, i.e. $I_1 = 6.25 \text{ A}$ can be determined using Δi_L as:

$$\Delta i_L = \frac{DV_S(1-D)T}{L} \implies L = \frac{DV_S(1-D)}{f\Delta i_L} = \frac{0.5 \times 50(1-0.5)}{100 \times 10^3 \times 2.5} = 50 \mu\text{H}$$

d) The value of C to limit the output voltage ripple to 0.5%.

The value of the capacitor C to limit the voltage ripple to 0.5%, i.e. $\Delta v_O = 0.005$ can be determined as:

$$\Delta v_O = \frac{(1-D)V_O}{8LCf^2} \implies C = \frac{(1-D)V_O}{8L\Delta v_O f^2} = \frac{(1-0.5) \times 25}{8 \times 50 \times 10^{-6} \times 0.005 \times (100 \times 10^3)^2} = 625 \mu\text{F}$$

Q3:

A DC boost converter has a supply voltage of 5 V, and an output voltage of 15 V to feed a load with 25 W. If the switching frequency is 300 kHz, determine:

a) The value of L that limit the minimum inductor current to 50% of the average current.

The average value of the load current I_O can be determined from V_O and the load power

P_L as:

$$P_L = V_O I_O \implies I_O = \frac{P_L}{V_O} = \frac{25}{15} = 1.6667 \text{ A}$$

The minimum inductor current $I_2 = 0.5I_O$, where:

$$I_2 = 0.5I_O = I_O - \frac{\Delta i_L}{2} \implies \Delta i_L = 2 \times 0.5I_O = 2 \times 0.5 \times 1.6667 = 1.6667 \text{ A}$$

The value of the inductor L can be determined using Δi_L as:

$$\Delta i_L = \frac{DV_S}{fL} \implies L = \frac{DV_S}{f\Delta i_L}$$

The value of the duty cycle D can be determined using V_O and V_s as:

$$\frac{V_O}{V_s} = \frac{1}{1-D} \implies \frac{15}{5} = \frac{1}{1-D} \implies 1-D = \frac{1}{3} \implies D = \frac{2}{3} = 0.6667$$

The value of the inductor L can be evaluated as:

$$L = \frac{DV_S}{f\Delta i_L} = \frac{0.6667 \times 5}{300 \times 10^3 \times 1.6667} = 6.667 \mu\text{H}$$

b) The duty cycle D .

The value of the duty cycle D can be determined using V_O and V_s as:

$$\frac{V_O}{V_s} = \frac{1}{1-D} \implies \frac{15}{5} = \frac{1}{1-D} \implies 1-D = \frac{1}{3} \implies D = \frac{2}{3} = 0.6667$$

c) The minimum values of L and C to ensure the converter is in the continuous mode.

The minimum value of the inductor L_B can be determined as:

$$L_B = \frac{D(1 - D)^2 R_L}{2f}; \quad R_L = \frac{V_O^2}{P_L} = \frac{15^2}{25} = 9 \quad \Omega$$

$$L_B = \frac{0.6667 \times (1 - 0.6667)^2 \times 9}{2 \times 300 \times 10^3} = 1.11 \quad \mu H$$

The minimum value of the capacitor C_B can be determined as:

$$C_B = \frac{D}{2fR_L} = \frac{0.6667}{2 \times 300 \times 10^3 \times 9} = 0.13 \quad \mu F$$

- d) The value of current ripple in the inductor, and the value of the voltage ripple in the capacitor.

The value of Δi_L was determined as:

$$\Delta i_L = 2 \times 0.5 I_O = 2 \times 0.5 \times 1.6667 = 1.6667 A$$

The value of Δv_O can be determined as:

$$\Delta v_O = \Delta v_C = \frac{I_O D}{f C} = \frac{1.66667 \times 0.66667}{300 \times 10^3 \times 10 \times C_B}$$

Please note that since the converter is in the continuous mode ($L > L_B$), then

let $C = 10C_B = 1.3 \mu F$

$$\Delta v_O = \Delta v_C = \frac{1.66667 \times 0.66667}{300 \times 10^3 \times 1.3 \times 10^{-6}} = 2.85 \quad V$$

Q4

Design a Buck-boost DC converter to supply a load with 75 W at 50 V from a 40 V supply.

The output voltage ripple $\Delta v_O \leq 1\%$. Specify the values of D , L , C , and switching frequency.

The duty cycle D can be determined using V_O and V_s as:

$$\frac{V_O}{V_s} = \frac{D}{1-D} \Rightarrow \frac{50}{40} = \frac{D}{1-D} \Rightarrow 1.25 - 1.25D = D \Rightarrow D = \frac{1.25}{2.25} = 0.5556$$

The average value of the load current I_O can be determined using V_O and P_L as:

$$I_O = \frac{P_L}{V_O} = \frac{75}{50} = 1.5 \text{ A}$$

The value of the capacitor C can be determined using $\Delta v_C = \Delta v_O$ and the switching frequency f as:

$$\Delta v_C = \Delta v_O = \frac{DI_O}{fC} \Rightarrow C = \frac{DI_O}{f\Delta v_O} = \frac{0.55556 \times 1.5}{0.01f}$$

Select $f = 250$ kHz.

$$C = \frac{0.55556 \times 1.5}{0.01 \times 250 \times 10^3} = 312 \mu F$$

In order to investigate the mode of operation, the value of C_B is determined and compared with C . The value of C_B is determined as:

$$C_B = \frac{DI_O}{2fV_O} = \frac{0.5556 \times 1.5}{2 \times 250 \times 10^3 \times 50} = 0.003 \mu F$$

Since $C > C_B$, the converter is in the continuous mode. The value of L can be determined using L_B as:

$$L_B = \frac{(1-D)V_O}{2fI_O} = \frac{(1-0.55556)50}{2 \times 250 \times 10^3 \times 1.5} = 29.63 \mu H$$

Let $L = 5L_B = 150 \mu H$.

Q5

A DC flyback converter has an input of 24 V to supply an output with 40 W at 40 V. If the output voltage ripple is limited to 0.5% and the ripple in the inductor current to 0.3% of the output average current, determine:

- The duty cycle D , and switching frequency.

In this case, the flyback converter can be approximated by the function of the DC boost converter. The duty cycle D can be approximated using the boost converter input/output relationship as:

$$D = 1 - \frac{V_s}{V_O} = 1 - \frac{24}{40} = 0.4$$

For the switching frequency f , set $f = 150$ kHz.

- The transformer turns ratio.

The turns ratio N_2/N_1 can be determined as:

$$\frac{N_2}{N_1} = \frac{V_O(1 - D)}{DV_s} = \frac{40(1 - 0.4)}{0.4 \times 24} = 2.5$$

- The value of L .

The value of L can be determined as:

$$L = \frac{V_s D}{f \Delta i_L}$$

The value of $\Delta i_L = 0.003I_O$, which can be determined as:

$$\Delta i_L = 0.003 \times \frac{P_L}{V_O} = 0.003 \times \frac{40}{40} = 0.003 \times 1 = 0.003 \text{ A}$$

$$L = \frac{24 \times 0.4}{150 \times 10^3 \times 0.003} = 21.3 \text{ mH}$$

d) The value of C .

The value of C can be determined as:

$$C = \frac{DI_O}{f\Delta v_C} = \frac{0.4 \times 1}{150 \times 10^3 \times 0.005} = 533.33 \text{ } \mu F$$

ECE 4643: Power Electronics

Exam 1: Solution

Time: Monday 21st, 2019, 10:30-11:25 AM

Instructor: Dr. S. A. Saleh

Q1 [5 marks]

Q1.1-

Q1.2-

Q2 [4 marks]

A 3 ϕ full-wave rectifier supplies an inductive load that has $R_L = 9 \Omega$ and $L_L = 3 \text{ mH}$. The input AC voltage is supplied from a feeder at 340 V, 60 Hz. Design an input LC filter that will ensure an input ripple factor of $RF \leq 6\%$, and an output LC filter for a ripple voltage $\Delta v_o \leq 5\%$. [2 marks].

The output DC voltage V_{dc} can be determined for the load as:

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_m$$

The feeder voltage is an rms line-to-line voltage (default specifications). The required the peak line-to-neutral value V_m :

$$V_m = \sqrt{2} \left(\frac{V_s}{\sqrt{3}} \right) = 277.61 \text{ V}$$

V_{dc} becomes:

$$V_{dc} = \frac{3\sqrt{3}}{\pi} \times 277.61 = 459.16 \text{ V}$$

The output DC current I_{dc} is determined as:

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{459.16}{9} = 51.02 \text{ A}$$

The input LC Filter

The values of the input filter parameters (L_S and C_S) can be determined based on the the value of the RF as:

$$\frac{X_{Ls}}{X_{Cs}} = \frac{1}{5^2} \left(\frac{I_{an}(n\omega)}{(I_{an}(n\omega))_{Ls}} + 1 \right) = \frac{1}{25} (RF + 1) = 0.04 \times (0.06 + 1) = 0.0424$$

Let $C_S = 30\mu\text{F}$. This value produces L_S as:

$$2\pi \times 60L_S = 0.0424X_{Cs} = \frac{0.0424}{2\pi \times 60 \times 30 \times 10^{-6}} = 3.75 \Rightarrow L_S = 10 \text{ mH}$$

The output C Filter

The value of the output side capacitor C_O can be determined using the ripple voltage conditions as:

$$C_O = \frac{100 (I_o(n=6))_{peak}}{\sqrt{2} \times (\Delta v_O\%) \times V_{dc} \times 12\pi \times f_s}$$

The peak value of the 6th harmonic voltage is:

$$(v_o(n=6))_{peak} = 0.9549V_m \times \frac{2}{35} = 0.9549 \times 277.61 \times 0.0571 = 15.12 \text{ V}$$

The peak value of $I_o(n=6)$ can be determined as:

$$(I_o(n=6))_{peak} = \frac{(v_o(n=6))_{peak}}{Z_L(6f_s)} = \frac{15.12}{\sqrt{R_L^2 + (2\pi \times 6f_s L_L)^2}} = 1.34 \text{ A}$$

The value of C_O can be determined as:

$$C_O = \frac{100 \times 1.34}{\sqrt{2} \times 5 \times 459.16 \times 2 \times 6 \times \pi \times 60} = 18.27 \text{ } \mu\text{F}$$

Q3 [6 marks]

A 3 ϕ full-wave rectifier supplies a resistive load with $R_L = 10 \Omega$. The input AC voltage is supplied from a Y-connected feeder at 208 V, 60 Hz. For this rectifier, determine:

a) The output DC voltage [1 marks].

The rms value of the phase voltage is $V_{sP} = \frac{208}{\sqrt{3}} = 120 \text{ V}$, $(V_m)_{peak} = \sqrt{2} \times V_{sP} = 169.7 \text{ V}$. The output DC voltage is obtained is:

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} = 1.654 \times 169.7 = 280.68 \text{ V}$$

b) $(I_O)_{rms}$ and I_{dc} [3 marks].

The rms output voltage is determined as:

$$(V_O)_{rms} = \sqrt{3} (V_m)_{Ph} \sqrt{\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}} = \sqrt{3} \times 169.7 \sqrt{0.5 + 0.4135} = 280.93 \text{ V}$$

$$(I_O)_{rms} = \frac{(V_O)_{rms}}{R_L} = \frac{280.93}{10} = 28.093 \text{ A}$$

The output DC current I_{dc} is:

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{280.68}{10} = 28.068 \text{ A}$$

c) The current in each diode [1 marks].

The average current in each diode I_D is determined as:

$$I_D = \frac{I_{dc}}{3} = \frac{28.068}{3} = 9.36 \text{ A}$$

d) The input power factor [1 marks].

The input power factor can be determined as:

$$PF = \frac{P_{dc}}{S_{in}} = \frac{V_{dc}I_{dc}}{\sqrt{3}V_sI_s}$$

The input current $(I_s)_{rms}$ can be determined as:

$$(I_s)_{rms} = (I_O)_{rms} \times \sqrt{\frac{2}{3}} = 28.093 \times 0.8165 = 22.94 \text{ A}$$

$$PF = \frac{P_{out}}{\sqrt{3}(V_{sL})_{rms}(I_{sL})_{rms}} = \frac{280.68 \times 28.068}{\sqrt{3} \times 208 \times 22.94} = 0.9532 \text{ Lag}$$

ECE 4643: Power Electronics

Assignment 2: Solution

Q1:

Q2

A 1ϕ full-wave rectifier supplies an inductive load ($R_L = 4 \Omega$ and $L_L = 9 \text{ mH}$) from a 60 Hz AC supply. Design an input LC filter that will limit the RF to $RF \leq 6\%$, and an output LC filter that will allow a voltage ripple as $\Delta v_o \leq 5\%$.

The input LC Filter

The values of the input filter parameters (L_S and C_S) can be determined based on the value of the THD_I or the RF as:

$$\frac{X_{Ls}}{X_{Cs}} = \frac{1}{3^2} \left(\frac{I_{an}(n\omega)}{(I_{an}(n\omega))_{Ls}} + 1 \right) = \frac{1}{9}(RF + 1) = 0.111 \times (0.06 + 1) = 0.118$$

Let $C_S = 30\mu\text{F}$. This value produces L_S as:

$$2\pi \times 60L_S = 0.118X_{Cs} = \frac{0.118}{(2\pi)^2 \times 60^2 \times 30 \times 10^{-6}} = 10.4332 \implies L_S = 27.7 \text{ mH}$$

The ouput LC Filter

The value of the output side capacitor C_O can be determined as:

$$\sqrt{R_L^2 + (2\pi 2f_s L_L)^2} \gg \frac{1}{2\pi 2f_s C_O}$$

$$\sqrt{16 + 46.0476} = \frac{8}{240\pi C_O} \implies C_O = 1300 \mu\text{F}$$

The value of L_O can be determined for the 2nd harmonic on the output as:

$$\Delta v_o = \left| \frac{-1}{(2\pi 2f_s)^2 L_O C_O - 1} \right| \implies (240\pi)^2 L_O C_O - 1 = \frac{1}{\Delta v_o}$$

$$L_O = \frac{\frac{1}{\Delta v_o} + 1}{(240\pi)^2 C_O} = \frac{1/0.05 + 1}{(240\pi)^2 \times 0.0013}$$

get $L_O = 28.4$ mH.

Q3:

A 3 ϕ full-wave rectifier supplies a 25 kW, 300 Vdc load. If this rectifier is supplied from a 3 ϕ 60 Hz feeder determine:

a) The input AC line and phase rms and peak voltages

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_m \implies V_m = \frac{300 \times \pi}{3\sqrt{3}} = 181.38 \text{ V}$$

The rms value for the input voltage phase voltage is $181.38/\sqrt{2} = 128.26$ V. The line voltage peak and rms values are:

$$V_L = \sqrt{3} \times 128.26 = 222.15 \text{ V}, \quad (V_L)_{peak} = \sqrt{3} \times 181.38 = 314.16$$

b) The values of $(I_O)_{rms}$, I_{dc} , and $(I_s)_{rms}$.

The value of $(I_O)_{rms}$ can be determined as:

$$(I_O)_{rms} = \frac{V_{Orms}}{R_L}; \quad R_L = \frac{V_{dc}^2}{P_O} = \frac{300^2}{25000} = 3.6 \Omega$$

The value of V_{Orms} can be determined as:

$$V_{rmso} = 1.654 V_m = 1.654 \times 181.38 = 300.0 \text{ V}$$

$$(I_O)_{rms} = \frac{300.0}{3.6} = 83.33 \text{ A}$$

The dc current demand of the load I_{dc} is determined as:

$$I_{dc} = \frac{P_L}{V_{dc}} = \frac{25 \times 10^3}{300} = 83.33 \text{ A}$$

The rms value of the input current $(I_s)_{rms}$ can be determined as:

$$(I_s)_{rms} = \sqrt{\frac{2}{3}} (I_O)_{rms} = \sqrt{\frac{2}{3}} \cdot 83.33 = 68.04 \text{ A}$$

c) The values for average and rms currents per diode. The average current in each diode:

The dc current demand of the load I_{dc} is determined as:

$$I_{dc} = \frac{P_L}{V_{dc}} = \frac{25 \times 10^3}{300} = 83.333 \text{ A}$$

The average current per-diode is determined as:

$$(I_D)_{avg} = \frac{I_{dc}}{3} = \frac{83.333}{3} = 27.78 \text{ A}$$

The rms value of the current through each diode is:

$$(I_D)_{rms} = \frac{(I_{rms})_o}{\sqrt{3}} = \frac{83.38}{\sqrt{3}} = 48.14 \text{ A}$$

d) PIV for each diode.

The peak inverse voltage for each diode (PIV) is:

$$PIV = \sqrt{2} \times (V_s)_{LL} = \sqrt{2} \times 222.15 = 314.16 \text{ V}$$

e) peak-to-peak ripple in $v_O(t)$ and its frequency.

The output voltage fluctuates between $1.225 (V_s)_{LL}$ and $\sqrt{2} (V_s)_{LL}$ as:

$$\left((v_{ripple}(t))_{out} \right)_{min} = 1.225 \times 222.15 = 272.13 \text{ V}, \text{ and } \left((v_{ripple}(t))_{out} \right)_{max} = \sqrt{2} \times 222.15 = 314.16$$

The peak value of the output voltage ripple is:

$$\left((v_{ripple}(t))_{out} \right)_{max} - \left((v_{ripple}(t))_{out} \right)_{min} = 314.16 - 272.13 = 42.03 \text{ V}$$

This ripple will have a fundamental frequency of $(f_{ripple})_1$ as:

$$(f_{ripple})_1 = 6 \times f_s = 6 \times 60 = 360 \text{ Hz}$$

Q4

A 3ϕ full-wave rectifier supplies an inductive load $R_L = 9 \Omega$ and $L_L = 3 \text{ mH}$. The input AC voltage is supplied from a feeder at 660 V, 60 Hz. Design an input LC filter that will ensure an input side RF of $RF \leq 6\%$, and an output LC filter for a ripple voltage $\Delta v_o \leq 8\%$.

The output DC voltage V_{dc} can be determined for the load as:

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_m$$

The feeder voltage is an rms line-to-line voltage (default specifications). The required the peak line-to-neutral value V_m :

$$V_m = \sqrt{2} \left(\frac{V_s}{\sqrt{3}} \right) = 538.8877 \text{ V}$$

V_{dc} becomes:

$$V_{dc} = \frac{3\sqrt{3}}{\pi} \times 538.8877 = 891.31 \text{ V}$$

The output DC current I_{dc} is determined as:

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{891.31}{9} = 99.03 \text{ A}$$

The input LC Filter

The values of the input filter parameters (L_S and C_S) can be determined based on the value of the THD_I or the RF as:

$$\frac{X_{Ls}}{X_{Cs}} = \frac{1}{5^2} \left(\frac{I_{an}(n\omega)}{(I_{an}(n\omega))_{Ls}} + 1 \right) = \frac{1}{25} (RF + 1) = 0.04 \times (0.06 + 1) = 0.0424$$

Let $C_S = 70\mu\text{F}$. This value produces L_S as:

$$2\pi \times 60L_S = 0.0424X_{Cs} = \frac{0.0424}{2\pi \times 60 \times 70 \times 10^{-6}} = 1.6067 \Rightarrow L_S = 4.26 \text{ mH}$$

The ouput LC Filter

The value of the output side capacitor C_O can be determined using the ripple voltage conditions as:

$$C_O = \frac{100 (I_o(n=6))_{peak}}{\sqrt{2} \times (\Delta v_O\%) \times V_{dc} \times 12\pi \times f_s}$$

The peak value of the 6th harmonic voltage is:

$$(v_o(n=6))_{peak} = 0.9549V_m \times \frac{2}{35} = 0.9549 \times 538.8877 \times 0.0571 = 29.38 \text{ V}$$

The peak value of $I_o(n = 6)$ can be determined as:

$$(I_o(n = 6))_{peak} = \frac{(v_o(n = 6))_{peak}}{Z_L} = \frac{29.38}{\sqrt{9^2 + (2\pi \times 6 \times 60 \times 0.003)^2}} = 2.6066 \text{ A}$$

The value of C_O can be determined as:

$$C_O = \frac{100 \times 2.6066}{\sqrt{2} \times 8 \times 891.31 \times 2 \times 6 \times \pi \times 60} = 11.43 \mu F$$

The value of L_O can be determined for the 6th harmonic on the output as:

$$\Delta v_o = \left| \frac{-1}{(2\pi 6 f_s)^2 L_O C_O - 1} \right| \Rightarrow (720\pi)^2 L_O C_O - 1 = \frac{1}{\Delta v_o}$$

$$L_O = \frac{\frac{1}{\Delta v_o} + 1}{(720\pi)^2 C_O} = \frac{1/0.08 + 1}{(720\pi)^2 \times 23.89 \times 10^{-6}}$$

get $L_O = 231 \text{ mH}$.

Q5

A 3 ϕ full-wave controlled rectifier supplies a resistive load with 12 kW at 80% of the maximum possible output DC voltage. The input AC voltage is supplied from a Δ -connected feeder at 340 V, 60 Hz. For this controlled rectifier, determine:

a) The firing angle α .

The Δ -connected feeder will include a $\Delta - Y$ transformer, where the Y -connected side will feed the AC-DC converter. The phase voltage is $V_{sP} = 340/\sqrt{3} = 196.3 \text{ V}$, $(V_m)_{peak} = \sqrt{2} \times V_{sP} = 277.61 \text{ V}$. The maximum possible output DC voltage is obtained for $\alpha = 0$ as:

$$(V_{dc})_{max} = \frac{3\sqrt{3}V_m}{\pi} \cos(\alpha = 0) = 1.654 \times 277.61 = 459.17 \text{ V}$$

The firing angle α can be determined from the required DC voltage, which is

$0.8 (V_{dc})_{max} = 367.33$ V. For the output DC voltage:

$$\alpha = \cos^{-1} \left(\frac{367.33}{459.61} \right) = 36.94^\circ$$

b) $(I_O)_{rms}$ and I_{dc} .

The rms output voltage is determined as:

$$(V_O)_{rms} = \sqrt{3} (V_m)_{Ph} \sqrt{\frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos(2\alpha)} = \sqrt{3} \times 277.61 \sqrt{0.5 + 0.4135 \cos(2 \times 34.86^\circ)} = 377.0 \text{ V}$$

$$(I_O)_{rms} = \frac{(V_O)_{rms}}{R_L}; R_L = \frac{V_{dc}^2}{P_o} = \frac{367.33^2}{12000} = 11.24 \Omega$$

$$(I_O)_{rms} = \frac{(V_O)_{rms}}{R_L} = \frac{377}{11.24} = 33.53 \text{ A}$$

The output DC current I_{dc} is:

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{367.33}{11.24} = 32.68 \text{ A}$$

c) The current in each thyristor.

The average current in each thyristor I_T is determined as:

$$I_T = \frac{I_{dc}}{3} = \frac{32.68}{3} = 10.89 \text{ A}$$

d) the efficiency of this controlled rectifier.

The efficiency η is determined as:

$$\eta = \frac{V_{dc} \times I_{dc}}{(V_O)_{rms} \times (I_O)_{rms}} = \frac{367.33 \times 32.68}{377 \times 33.53} = 94.96\%$$

e) The input power factor.

The input current $(I_s)_{rms}$ can be determined as:

$$(I_s)_{rms} = (I_O)_{rms} \times \sqrt{\frac{2}{3}} = 33.53 \times 0.8165 = 27.35 \text{ A}$$

The output power $P_{out} = 12 \text{ kW}$. The input power factor is determined as:

$$PF = \frac{P_{out}}{\sqrt{3} (V_s)_{rms} \times (I_s)_{rms}} = \frac{12000}{\sqrt{3} \times 340 \times 27.35} = \frac{12}{22.613} = 0.745 \text{ Lag}$$

f) The commutation angle u .

From the output DC voltage:

$$V_{dc} = \frac{3(V_{LL})_{Peak}}{2\pi} (\cos(\alpha) + \cos(\alpha + u)); 367.33 = \frac{3 \times \sqrt{2} \times 340}{2\pi} (\cos(36.94) + \cos(36.94 + u))$$

$$\cos(36.94 + u) = 0.8008 \implies u = -0.15^\circ \approx 0$$

Assignment 1: Solutions

Q1:

Q2 Consider the converter shown in Figure 1. Assume that the MOSFET Q and diode D are ideal in that their ON-state voltages are zero, and they can turn turn-ON and turn-OFF instantly. The waveform of the diode switching is also included in Figure 1.

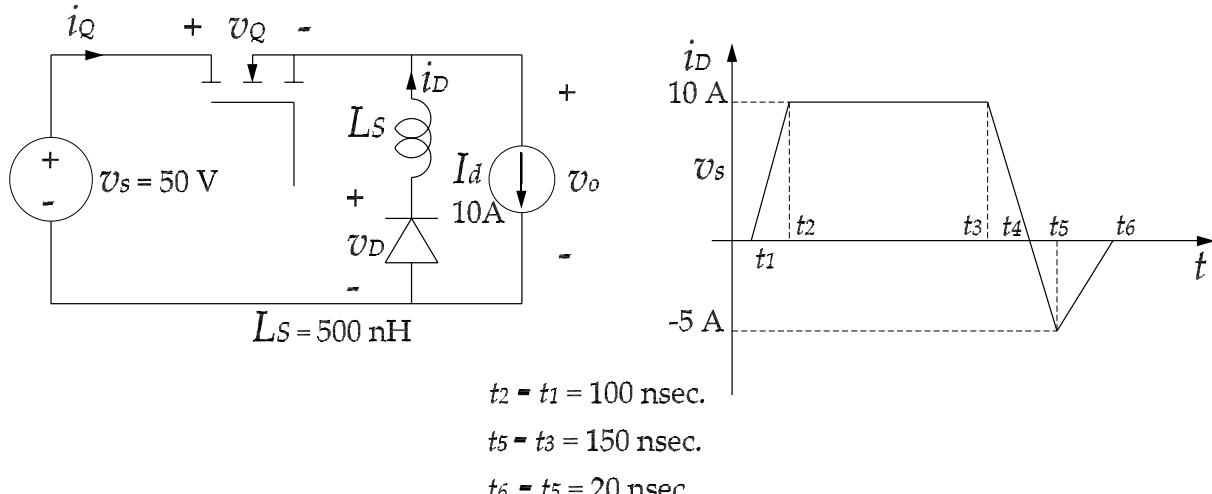


Figure 1: The converter for Q2.

1. Calculate and sketch to scale the diode and MOSFET voltages v_D and v_Q , and i_Q ;

The waveforms of i_D , v_D , v_Q , and i_Q are shown in Figure 2.

2. Estimate the switching losses in the diode and the MOSFET if the converter is operated at a switching frequency of $f_s = 200 \text{ kHz}$.

The switching losses will be determined for ON and OFF switching for both D and Q .

- (a) **D:** The instantaneous ON switching losses $(P_{ON1})_D$ are determined as:

$$(P_{ON1})_D = v_D(t)i_D(t); v_D(t) = v_s \left(1 - \frac{t}{t_2}\right); i_D(t) = \frac{I_d}{t_2}t$$

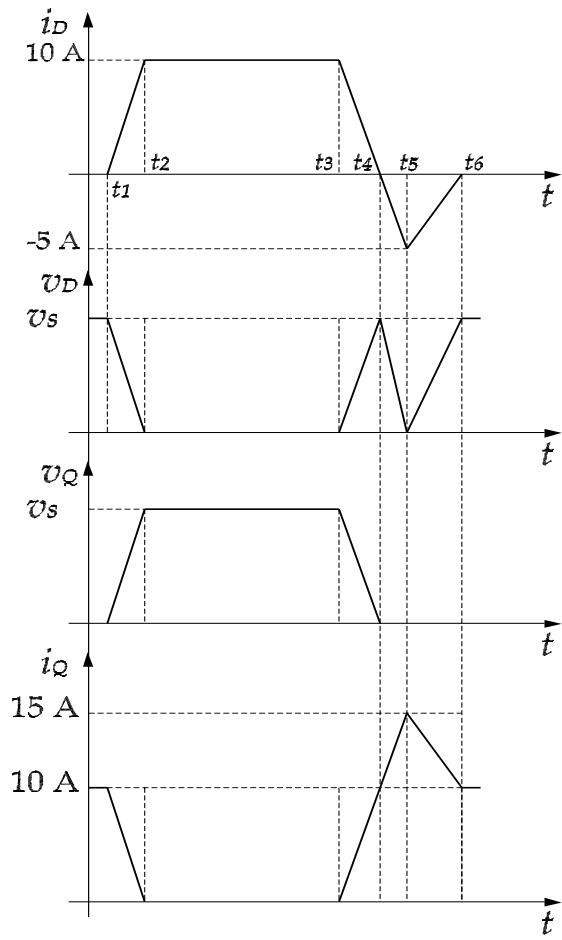


Figure 2: The waveforms of i_D , v_D , v_Q , and i_Q .

$$(P_{ON1})_D = \frac{v_s I_d}{t_2} t - \frac{v_s I_d}{t_2^2} t^2$$

The energy losses during ON switching $(W_{ON})_D$ is determined as:

$$(W_{ON})_D = \int_0^{t_2} (P_{ON1})_D dt = \int_0^{t_2} \frac{v_s I_d}{t_2} t dt - \int_0^{t_2} \frac{v_s I_d}{t_2^2} t^2 dt = \frac{v_s I_d}{2} t_2 - \frac{v_s I_d}{3} t_2^2$$

The average power losses during ON switching $(P_{ON})_D$ is determined as:

$$(P_{ON})_D = (W_{ON})_D \times f_s = 1.6667 \text{ W}$$

The instantaneous OFF switching power losses $(P_{OFF1})_D$ are determined as:

$$(P_{OFF1})_D = v_D(t)i_D(t);$$

During the OFF switching $i_D(t)$ has 2 portions, which can be expressed as:

$$(i_D(t))_1 = I_d - \frac{I_d + 5}{t_5}t, \quad (i_D(t))_2 = \frac{5}{t_6}t - 5$$

$v_D(t)$ has 3 portions that can be expressed as:

$$(v_D(t))_1 = \frac{v_s}{t_4}t, \quad (v_D(t))_2 = v_s \left(1 - \frac{1}{t_5}t\right), \quad (v_D(t))_3 = \frac{v_s}{t_6}t$$

The energy losses during OFF switching $(W_{OFF})_D$ is determined as:

$$(W_{OFF})_D = \int_{t_3}^{t_4} (v_D(t))_1 (i_D(t))_1 dt + \int_{t_4}^{t_5} (v_D(t))_2 (i_D(t))_1 dt + \int_{t_5}^{t_6} (v_D(t))_3 (i_D(t))_2 dt$$

$$(W_{OFF})_D = \int_0^{t_4-t_3} (v_D(t))_1 (i_D(t))_1 dt + \int_0^{t_5-t_4} (v_D(t))_2 (i_D(t))_1 dt + \int_0^{t_6-t_5} (v_D(t))_3 (i_D(t))_2 dt$$

$$\begin{aligned} (W_{OFF})_D &= \frac{I_d v_s}{2t_4} (t_4 - t_3) - \left(\frac{I_d v_s + 5v_s}{3t_4 t_5} \right) (t_4 - t_3)^3 + v_s I_d (t_5 - t_4) - \left(\frac{I_d v_s + 5v_s}{2t_5} \right) (t_5 - t_4)^2 \\ &\quad - \frac{I_d v_s}{2t_5} (t_5 - t_4)^2 + \left(\frac{I_d v_s + 5v_s}{3t_5^2} \right) (t_5 - t_4)^3 + \frac{5v_s}{3t_6^2} (t_6 - t_5)^3 - \frac{5v_s}{2t_6} (t_6 - t_5)^2 \end{aligned}$$

$$(W_{OFF})_D = 2.1307 \times 10^{-5} \text{ J}$$

Assuming that t_4 is the mid point between t_3 and t_5 , the average power losses during OFF switching $(P_{OFF})_D$ is determined as:

$$(P_{OFF})_D = (W_{OFF})_D \times f_s = 4.2614 \text{ W}$$

The switching power losses for D are $(P_{SW})_D$ is determined as:

$$(P_{SW})_D = (P_{ON})_D + (P_{OFF})_D = 5.9281 \text{ W}$$

(b) **Q:**

The instantaneous OFF switching losses $(P_{OFF1})_Q$ are determined as:

$$(P_{OFF1})_Q = v_Q(t)i_Q(t); \quad v_Q(t) = \frac{v_s}{t_2}t; \quad i_Q(t) = I_d \left(1 - \frac{t}{t_2}\right)$$

$$(P_{OFF1})_Q = \frac{v_s I_d}{t_2} t - \frac{v_s I_d}{t_2^2} t^2$$

The energy losses during OFF switching $(W_{OFF})_Q$ is determined as:

$$(W_{OFF})_Q = \int_0^{t_2} (P_{ON1})_Q dt = \int_0^{t_2} \frac{v_s I_d}{t_2} t dt - \int_0^{t_2} \frac{v_s I_d}{t_2^2} t^2 dt = \frac{v_s I_d}{2} t_2 - \frac{v_s I_d}{3} t_2$$

The average power losses during OFF switching $(P_{OFF})_Q$ is determined as:

$$(P_{OFF})_Q = (W_{OFF})_Q \times f_s = 1.6667 \text{ W}$$

The instantaneous ON switching power losses $(P_{ON1})_Q$ are determined as:

$$(P_{ON1})_Q = v_Q(t)i_Q(t);$$

$$i_Q(t) = \frac{I_d + 5}{t_5} t, \quad v_Q(t) = v_s \left(1 - \frac{t}{t_4}\right)$$

The value of $(P_{ON1})_Q$ is determined as:

$$(P_{ON1})_Q = \frac{15v_s}{t_5} t - \frac{15v_s}{t_4 t_5} t^2$$

The energy losses during ON switching $(W_{ON})_Q$ is determined as:

$$(W_{ON})_Q = \int_0^{t_4} (P_{ON1})_Q dt = \int_0^{t_4} \frac{15v_s}{t_5} t dt - \int_0^{t_4} \frac{15v_s}{t_4 t_5} t^2 dt = \frac{15v_s}{2t_5} t_4^2 - \frac{15v_s}{3t_5} t_4^2$$

Assuming that t_4 is the mid point between t_3 and t_5 , the average power losses during ON switching $(P_{ON})_Q$ is determined as:

$$(P_{ON})_Q = (W_{ON})_Q \times f_s = 0.9375 \text{ W}$$

The switching power losses for Q are $(P_{SW})_Q$ are determined as:

$$(P_{SW})_Q = (P_{ON})_Q + (P_{OFF})_Q = 2.61 \text{ W}$$

3. If the total losses for the MOSFET and diode are modeled as:

$$P_{LQ} = 20 + 50 \times 10^{-6} f_s \text{ and } P_{LD} = 10 + 0.44 \times 10^{-6} f_s$$

where f_s is the switching frequency. Determine the maximum switching frequency so that the junction temperature of both Q and D does not exceed 120 C°. Assume that both D and Q are mounted on the same heat sink, and the ambient temperature is 40 C°. The thermal resistances are in C°/W as:

$$(R_{\theta JC})_Q = 0.8, (R_{\theta CS})_Q = 1.2,$$

$$(R_{\theta JC})_D = 0.6, (R_{\theta CS})_D = 1.4,$$

$$R_{\theta SA} = 0.4$$

The equivalent thermal circuit for D , Q , cases, and the heat sinks are shown in Figure 3.

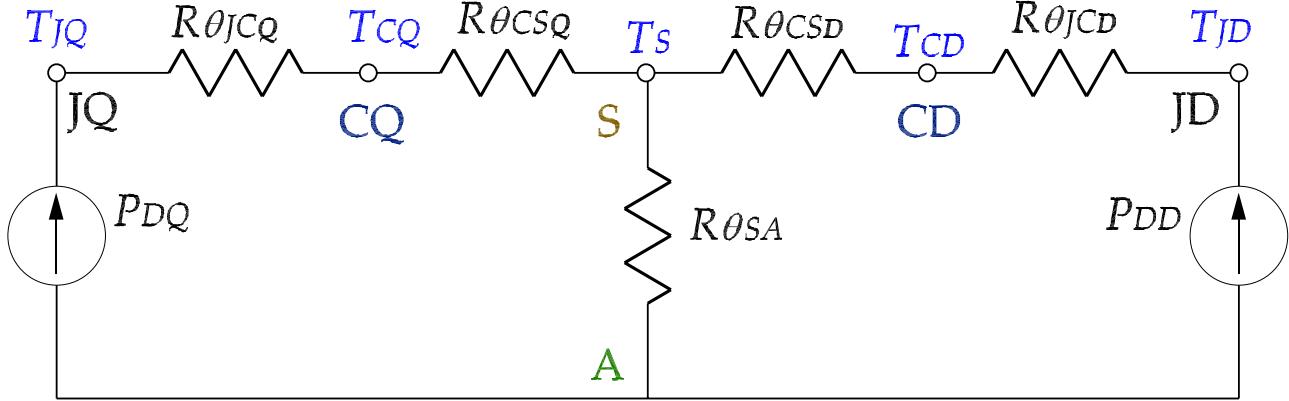


Figure 3: The thermal circuit for the Q2-3.

$$T_{JQ} - T_S = P_{LQ} \left((R_{\theta JC})_Q + (R_{\theta CS})_Q \right) \Rightarrow T_S = 120 - 2P_{LQ}$$

$$T_S - T_A = (P_{LQ} + P_{LD}) R_{\theta SA} \Rightarrow 120 - 2P_{LQ} - 40 = (30 + 50.44 \times 10^{-6} f_s) 0.4$$

$$80 - 40 - 100 \times 10^{-6} f_s = 12 + 20.176 \times 10^{-6} f_s \Rightarrow f_s = 232.997 \text{ kHz}$$

Q3: Design a BJT drive circuit with an initial base current of 5 A, for this BJT having $I_C = 25 \text{ A}$. This BJT is to be switched at a switching frequency $f_s = 8 \text{ kHz}$ with a duty cycle of 75%. This BJT has $h_{fe} = 30$, a drive signal is 10 V (ON), and $V_{BE(sat)} = 1 \text{ V}$.

The schematics of the driver is shown in Figure 4.

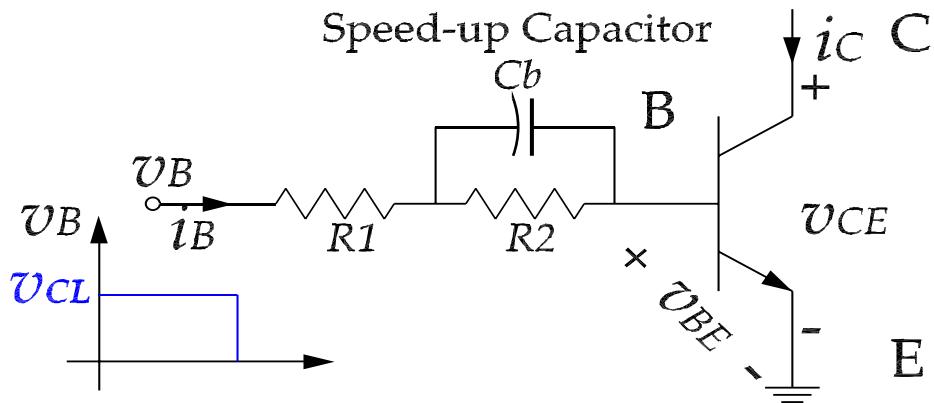


Figure 4: The desired drive circuit for the BJT

The initial base activation current $I_{B1} = 5$. The minimum current to ensure an ON state is I_{B2} that can be determined as:

$$I_{B2} = \frac{I_C}{h_{fe}} = \frac{25}{30} = 0.8333 \text{ A}$$

Assume overdrive required current I_{B2} as:

$$I_{B2} = 3 \times I_{B2} = 2.5 \text{ A}$$

$$I_{B1} = \frac{V_B - V_{BE}(sat)}{R_1} = \frac{10 - 1}{R_1} \implies R_1 = \frac{9}{5} = 1.8 \Omega$$

$$I_{B2} = \frac{V_B - V_{BE}(sat)}{R_1 + R_2} \implies R_2 = \frac{9}{2.5} - 1.8 = 1.8 \Omega$$

Assume charging time (5τ) to be $0.2T_{ON}$, the value of T_{ON} can be determined as:

$$D = \frac{T_{ON}}{T_s} = T_{ON} \times f_s \implies T_{ON} = \frac{0.75}{8000} = 93.75 \mu\text{sec.}$$

$$5\tau = 0.2 \times 93.75 \times 10^{-6} = 18.75 \times 10^{-6} \implies \tau = 3.75 \times 10^{-6} \text{ sec}$$

The value of C is determined as:

$$\tau = R_{eq}C; R_{eq} = R_1//R_2 = 0.9 \Omega$$

get the value of $C = 4.2\mu\text{F}$.