ENE505 Power Electronics for Renewable energy

Exam!

→ Possibility of making own assumptions if Necessary.
↳ This is done, be aware of these when correcting.

1) $V_{PV} = V_d$

DC-DC Buck/Boost Under Steady State.

$f_s = 400kHZ$ $T_s = \frac{1}{f_s} = 2,5 \mu S$

Design Criteria of the Buck/Boost Converter:

- $V_d = 12V$
- $D = 0,6$ ⇒ Boosting phase $D > 0,5$
- $P_o = 36W$ $(P_o = V_o \cdot I_o)$
- $L = 25 \mu H$

i)

$P = V \cdot I$

$V_d = 12$

$\Downarrow$

$$V_0 = \frac{D}{1-D} \cdot V_{in} = \frac{0,6}{1-0,6} \cdot 12 = \underline{18\,V}$$

⇒ Assuming ideal converter !!

$P_{in} = P_0 \Rightarrow \quad I_{in} = \frac{36}{12} = \underline{3\,A}$

$$I_0 = \frac{36}{18} = \underline{2\,A}$$

$I_L = I_{in} + I_0 = 5\,A$

$$\Delta i_L = \frac{1}{L} V_{in} \cdot (DT_s) = \frac{1 \cdot 12 \cdot 0,6 \cdot 2,5 \cdot 10^{-6}}{25 \cdot 10^{-6}} = \underline{0,72\,A}$$

$\underline{\Delta i_L = 0,72\,A}$ (half $= 0,36$)

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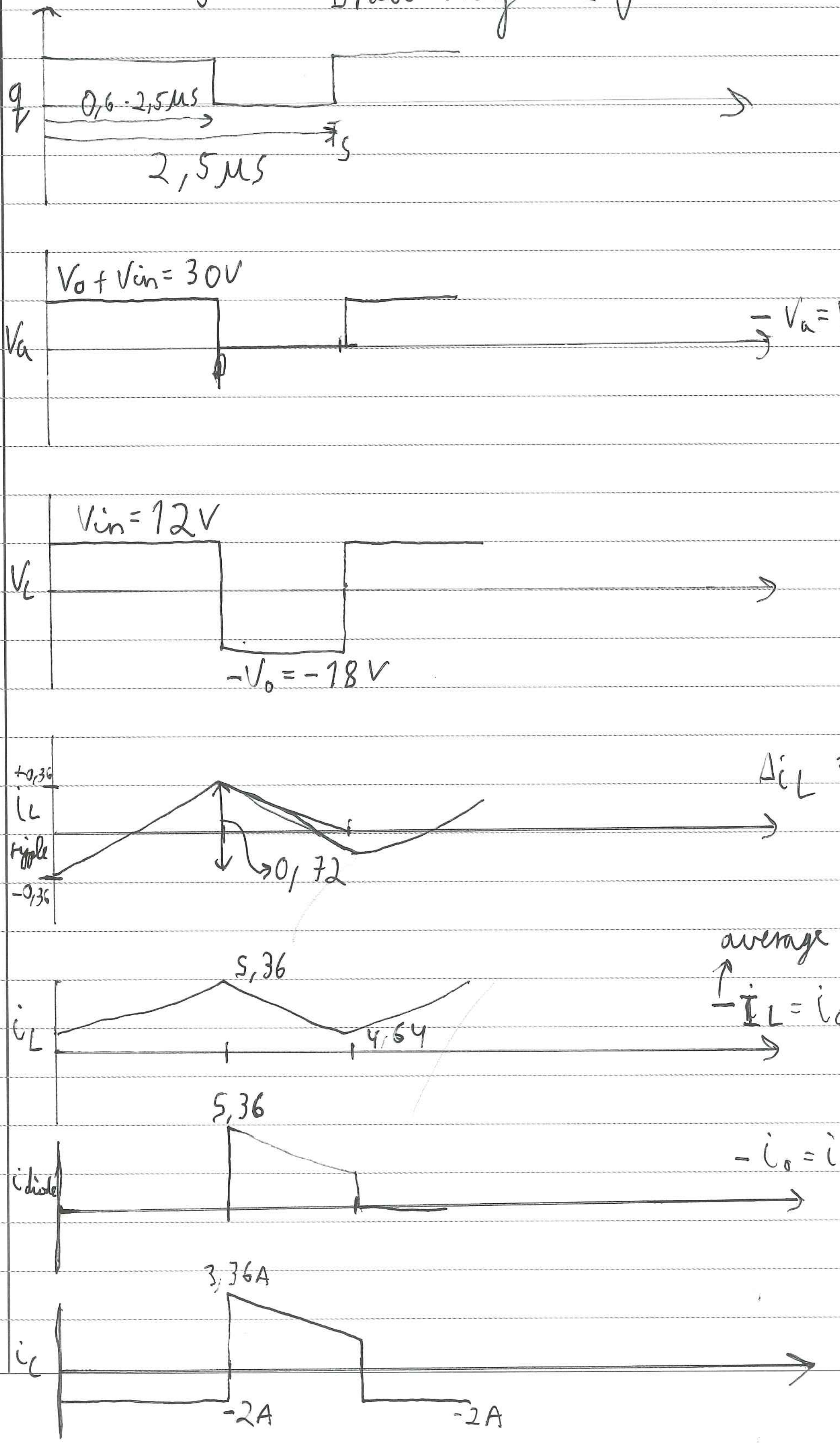
1i) Waveforms drawn: Buck/Boost Converter.

↳ Draw only one period



1ii) Changing output load!

Calculate P_o → Below this the converter will enter DCM.

↳ This means find the critical point for the design criteria.

Need to find the critical inductor current

$$I_{in} = \frac{D}{1-D} \cdot I_o \quad \Rightarrow \quad I_L = I_o + \frac{D}{1-D} I_o$$

$$I_{L,crit} = \frac{V_{in} \cdot D}{2 \cdot L \cdot f_s}$$

$$\Rightarrow \frac{12 \cdot 0{,}6}{2 \cdot 25 \cdot 10^{-6} \cdot 400000} = \underline{\underline{0{,}36\,A}}$$

⇒ This proves that $\frac{\Delta i_L \text{ ripple}}{2} = 0{,}36$ is the critical value of the inductor current.

$$I_o = \frac{I_L}{\left(1 + \frac{D}{1-D}\right)} = \frac{0{,}36}{\left(1 + \frac{0{,}6}{1-0{,}6}\right)} = \underline{\underline{0{,}144\,A}}$$

$$\Rightarrow P_o = 18 \cdot 0{,}144 = 2{,}6 \approx 2{,}6\,W$$

↳ At this point it will enter DCM below

↳ It is assumed same output voltage

1iii) $P_o = 5W$, What is critical inductor value? $L = ?$

$\Rightarrow I_o = \frac{5}{18} = 0,278\,A$

$\hookrightarrow I_L = 0,278 + \frac{0,6}{1-0,6} \cdot 0,278 = 0,695\,A$

$\hookrightarrow$ This is the critical value of inductor current

$$L = \frac{V_{in} \cdot D}{2 \cdot I_{L,crit} \cdot f_s}$$

$$L = \frac{12 \cdot 0,6}{2 \cdot 0,695 \cdot 400000} = 1,29 \cdot 10^{-5}$$

$\Downarrow$

13 μH

$\downarrow$

This is the critical value of inductor. Below this it will enter DCM with $P_o = 5W$.

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2 | 2.1 → It stands draw in text, but i assume here it is wanted the expressions for linearization

Designing feedback Controller.

→ When doing design of these DC-DC converters it is important to keep in mind the linearization procedure. This can be done through using the theory we have learned about these DC-DC-Converters.

To show how this can be done i will use an Buck converters theory as example. The linearization result is highly dependant of the type of converter analyzed, since they are all based on different theories

$$d(t) = D + \tilde{d}(t)$$

⇒ Neglect product of small perturbation terms!

Vin and Iin:

$$\bar{v}_{vp}(t) = V_{vp} + \tilde{v}_{vp}(t)$$

$$\bar{i}_{vp}(t) = I_{vp} + \tilde{i}_{vp}(t)$$

Vo and Io:

$$\bar{v}_{cp}(t) = V_{cp} + \tilde{v}_{cp}(t)$$

$$\bar{i}_{cp}(t) = I_{cp} + \tilde{i}_{cp}(t)$$

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2.1

Using Buck converter theory

$V_o = D \cdot V_{in}$ $\qquad$ $I_{in} = D \cdot I_o$

$$\left(V_{cp} + \tilde{v}_{cp}(t)\right) = \left(D + \hat{d}(t)\right)\left(V_{vp} + \tilde{v}_{vp}(t)\right)$$

$$V_{cp} + \tilde{v}_{cp}(t) = D V_{vp} + D\tilde{v}_{vp}(t) + \tilde{d}(t) \cdot V_{vp} + \tilde{d}(t) \cdot \tilde{v}_{vp}(t)$$

$$\Downarrow$$

$$\boxed{\tilde{v}_{cp}(t) = D\tilde{v}_{vp}(t) + \tilde{d}(t) \cdot V_{vp}}$$

→ Small signal perturbation for the voltage expressed by the the output voltage

→ Given by D and V_{vp}

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2.1

Now for the Current:

$$I_{in} = D \cdot I_o$$

$$\left(I_{cp} + \tilde{i}_{cp}(t)\right) = \left(D + \tilde{d}(t)\right)\left(I_{cp} + \tilde{i}_{cp}(t)\right)$$

$$\cancel{I_{cp}} + \tilde{i}_{cp}(t) = \cancel{D I_{cp}} + D\tilde{i}_{cp}(t) + \tilde{d}(t) \cdot I_{cp} + \cancel{\tilde{d}(t) \cdot \tilde{i}_{cp}(t)}$$

$$\Downarrow$$

$$\boxed{\tilde{i}_{cp}(t) = D i_{cp}(t) + \tilde{d}(t) \cdot I_{cp}}$$

→ Given by D and I_{cp}

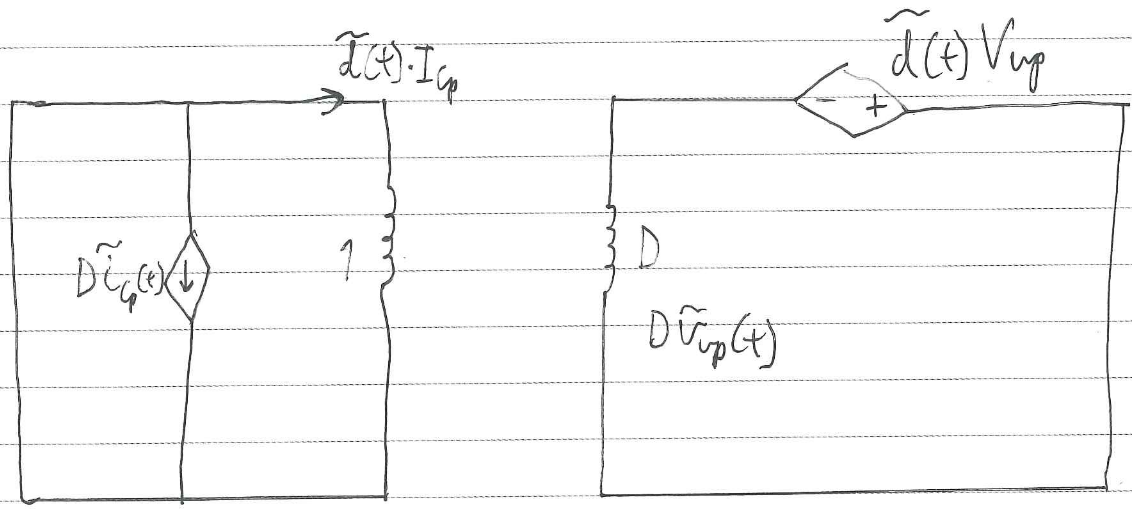
→ Small linearised expression for the change around DC steady state

⇒ These two expressions can be drawn see 2.2.

2.2

Using the previous expressions and transformer analogy the small change around DC steady state can be drawn as seen bellow.

↳ This only for being able to do construction of the feedback controller.



⇒ This above is an linearized single switch converter for a Buck converter, at least how I remember it at this point.

↳ Maybe something is missing, but the vital parts is included.

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3)
3.1) Single phase diode bridge rectifier

Operating conditions of Bridge: (lower power quality)

$I_s = 10A$ (rms)

$DPF = 0,85$

$I_{s1} = 8A$ (rms)

Calculations:

a) Distortion component of input current Idistortion.

$I_s^2 = I_{s1}^2 + I_{disto}^2$

$I_{disto} = \sqrt{I_s^2 - I_{s1}^2}$

$I_{distortion} = \sqrt{10^2 - 8^2} = \underline{6A}$

The distortion created by the rectifier bridge is 6 A. The supplied current I_s, will consist of all these I_{s1} and Idistortion

↳ Lowering the overall power factor.

⇒ The distortion current may cause damage to equipment, But it does always cause higher losses in the circuit

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b) Total Harmonic Distortion

THD

$$\%THD = \frac{I_{distortion}}{I_{s1}} \cdot 100$$

$$\%THD = \frac{6}{8} \cdot 100 = \underline{\underline{75\%}}$$

→ Preferably no THD is wanted in an electric circuit, at THD = 0% the DPF and PF is the same value, which is wanted at all times. Different measures can be taken in order to ensure this operation.

⇒ This rectifier bridge is not good directly coupled to the load.

c) Overall power factor of the load

$$PF = \frac{I_{s1}}{I_s} DPF$$

$$PF = \frac{8}{10} \cdot 0,85 = 0,68 \approx \underline{68\%}$$

(68% Active power
32% reactive power)

⇒ The overall power factor is 68%, preferably this is should have been at 100%, so this is a highly unwanted operation conditions. Measures should be taken!

→ a Boost Converter can be introduced in order to increase the overall power factor, this is a correction measure often introduced in order to keep it as high as possible

↳ See part 3.2 for operation principle.

There is too much reactive power, which cannot be utilized in any way and thus is a loss of power.

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3.2

See page 14 for drawing of the Circuit. (figure)

→ Assume that the PFC Circuit with its Corresponding Control System is the one asked about. (Block diagram on Control Circuit) This to be able to show where the signals is Collected from.

Explaination:

As mentioned earlier to correct the power factor an DC-DC Boost Converter is introduced see in figure. In order to Control this an outer and an inner loop is used. The outer loop is represented by voltage control. This Controller take a ref voltage and the real voltage, Compare them and supply a inductor current that is needed to keep or change the output voltage.
This value is than Compared with the real inductor value and supplied to the Current Controller, which use this error with output Current and than give an V_c signal to the PWM generator which supplies the switching signal to the switch.

Page 15 for more.

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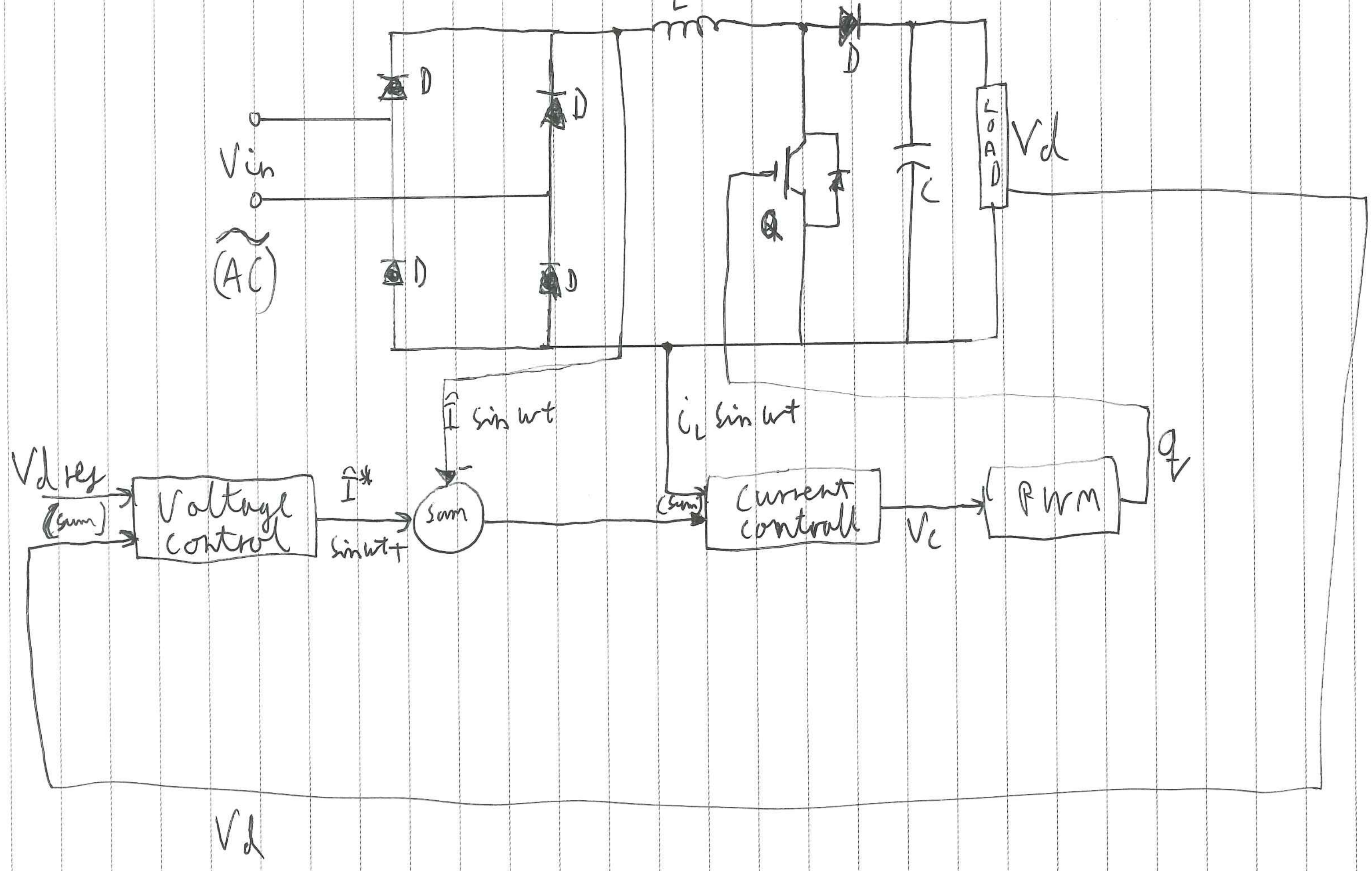

⇒ This control set-up ensure stabile and correct controlle with low overshoot and error, given correct control values.

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3.2

An very important design factor in these PFC circuits and controllers is that the outer voltage loop has much lower frequenly than the inner current loop. Often the current loop has frequenhy of 10kHZ and the voltage has 15HZ

↳ This is to keep stability and ensure that the values is kept at wanted positions at all times.

⇒ This PFC will supply an output current and voltage at much better PF unity than a single rectifier bridge without the Boost Converter.

→ Vin and Vd is out
↓
AC in DC out

↳ This way is often cheaper than doing something else.

4

4.1 A single phase AC-DC power factor correction converter. Boost!

Continous Conduction mode (CCM)

Varying $D \Rightarrow d(t)$ to keep $PF = 1$

$V_{in} = 120\ V\ rms \Rightarrow \hat{V} = 120 \cdot \sqrt{2} = 169{,}7\ V$

$f = 60\ Hz \Rightarrow w = 2 \cdot \pi \cdot 60 = 120\pi$

$v_{in} = 169{,}7 \cdot \sin(wt)$

Output voltage:

$V_o = V_d = 250\ V$ (DC)

Output power $= 300\ W$

→ Boost converter theory must be used!

$$V_o = \frac{1}{1-D} V_{in}$$

$I_{in} = I_L$

$$I_{in} = \frac{1}{1-D} I_o$$

4.1

The inductor current is:

$i_L(t) = i_{in}(t)$ → But rectified, due to the diode bridge

⇒ · Assuming unity power factor of supplied power!
· Assuming ideal converter to be able to do calculations

$P = I_{in} \cdot V_{in} \cdot \cos\phi$ → rms values

$$\Rightarrow I_{in} = \frac{300}{120} = 2{,}5A$$

$$i_{in}(t) = i_L(t) = 3{,}54 \sin(\omega t)$$

($3{,}54 \to \hat{I}_L$)

$$2{,}5 \cdot \sqrt{2} = 3{,}54\ A = \hat{I}_L$$

Duty ratio:

$$250 = \frac{1}{1-d(t)} \cdot 120 \cdot \sqrt{2} \cdot \sin(\omega t)$$

$$250 - 250\,d(t) = 120\sqrt{2} \cdot \sin(\omega t)$$

$$1 - d(t) = \frac{120 \cdot \sqrt{2}}{250} \sin(\omega t)$$

$$d(t) = 1 - \frac{120 \cdot \sqrt{2}}{250} \cdot \sin(\omega t)$$

4.7) Drawings of the currents and so on can be found on page 19.

Further calculations

The whole point of introducing the Boost Converter is to eliminate the ripple in the inductor current:

$$i_d(t) = \frac{1}{2}\frac{\hat{V}_{in}}{V_d}\hat{I}_L - \frac{1}{2}\frac{\hat{V}_{in}}{V_d}\hat{I}_L \cos(2\omega t) \quad \text{(Load Current)}$$

$\Downarrow$ I_d $\qquad$ $\Downarrow$ $i_{d2}(t) = i_c(t)$

$$I_d = \frac{1 \cdot 169{,}7}{2 \cdot 250} \cdot 3{,}54 = 1{,}2\ A$$ ⇒ output

$$i_{d2}(t) = i_c(t) = -\frac{1 \cdot 169{,}7}{2 \cdot 250} \cdot 3{,}54 \cos(2\omega t)$$

$$= -1{,}2 \cos(\omega t)\ A$$ (eliminated in capacitor)

⇒ In all these above expressions, the ω can be replaced with the real one

$\omega = 120\pi$ → Into all the the expressions
→ not doing this, but have understanding of it.

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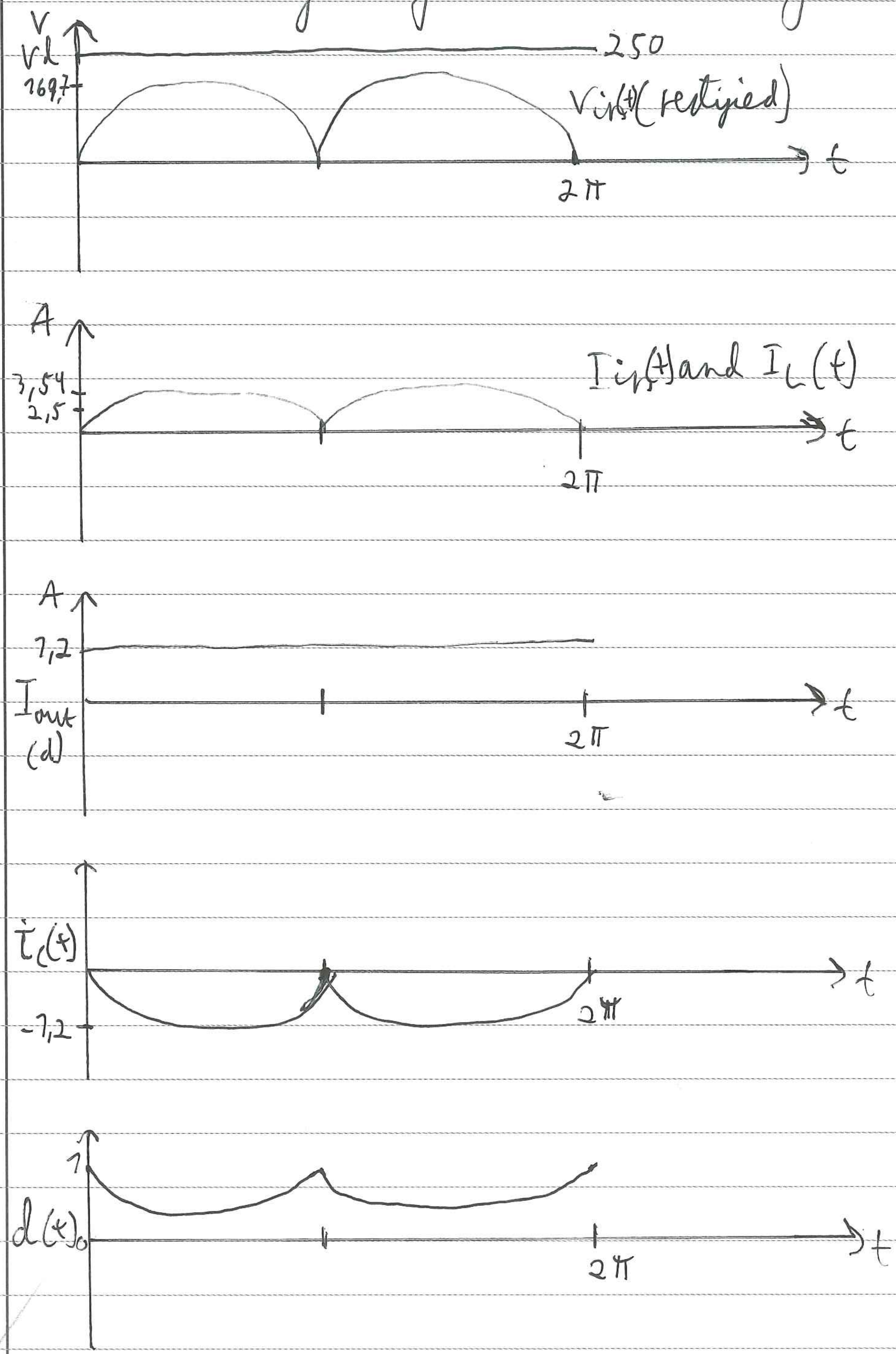
4.1) Drawings of the waveforms:



⇒ This is drawn for one period, to be able to provide an example on how it looks.

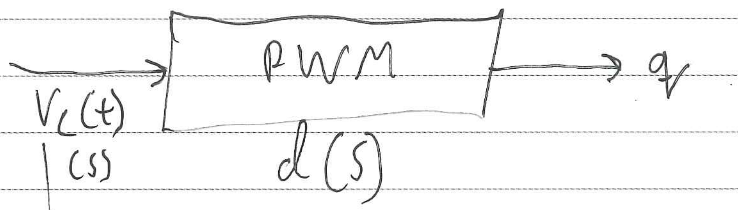
⇒ All synchronized to the Vin waveforms.

4.2

DC-DC converters are widely used in renewable energy systems, Their operation is controlled through the PWM operation block. Which supplies the control signal.

PWM Block

⇓



↳ Supplied by the error amplifier.

In a PWM block the signal V_c is compared with a sawtooth signal generated at an given frequency f_s.

→ See next page for figure.

↳ This is a genial way of constructing the changing control signal to the converter.

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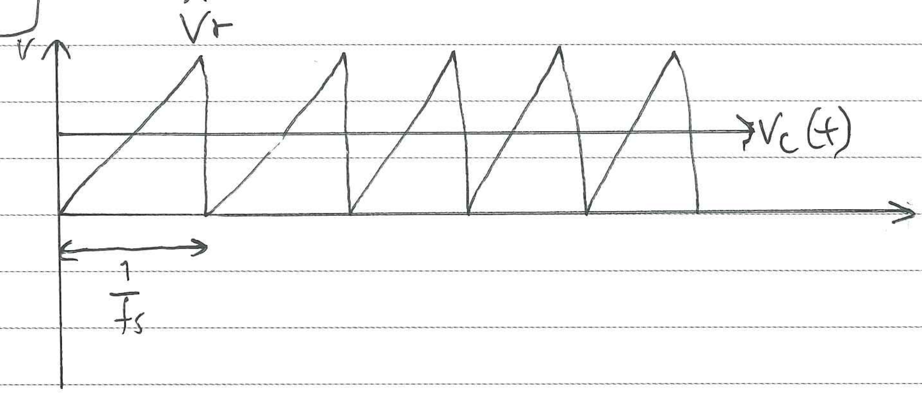
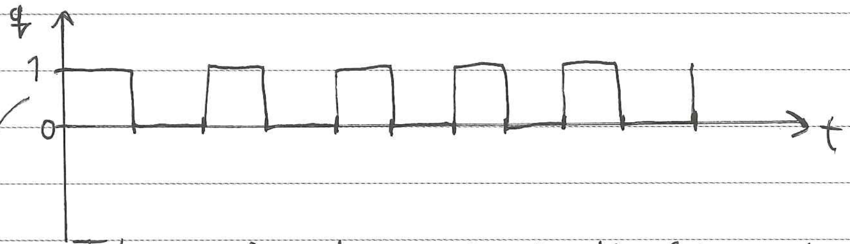
4.2

(sawtooth waveform)





→ This is the controll signal sent to to the switch and controls the whole circuit. If the V_c is changed it will move up or down and thus change the duty ratio and the voltage in the converter

In order to display this linearised we use:

$$G_{PWM} = \frac{d(s)}{V_c(s)} = \frac{1}{V_r}$$

This is linearized transfer function for the PWM Block in a DC-DC converter control system!