Re-exam

EPSH1/PED1/WPS1
2011
February 2012/CLB/SMN

Department of
ENERGY TECHNOLOGY
Aalborg University
E.T.

Written re-examination in

High Voltage Engineering and Design of Switch Mode Converters

Monday 27th of February 2012

09.00 – 13.00 (4 hours)

Please provide sufficient text description and reference to textbook and equations so your method of solution is clear and easy to follow. Statements and results will only give credit if explained thoroughly.

Both the HV part and the SMC part individually have to be passed in order to pass the course. This means that at least 50 % of both the HV exercise and the SMC exercise have to be correctly answered.

The HV exercise and the SMC exercise have the same weight.

Exercise 1 (High Voltage)

A company tests their dielectric materials by placing them in a test capacitor setup. Suppose you can assume that such capacitor is an ideal plate capacitor possessing a uniform field. In this exercise the dielectric material is inserted in the test capacitor in all questions a-e.

a) The test capacitor (including the dielectric material) has a capacitance C = 43,8 pF, a diameter D = 10 cm and a gap length d = 1 cm. Calculate the relative permittivity of the dielectric material assuming the capacitor is lossless.

b) The test capacitor is energized with DC High Voltage. The voltage is measured by means of a sphere gap. This sphere gap breaks down for a gap length (sphere diameter 12,5 cm) of 20 mm. The ground return current is measured with a precise ammeter to I = 12 pA (neglect all stray fields and creeping currents). Calculate the DC specific conductivity σ_0 of the dielectric material.

c) Now the test capacitor is tested with the Schering Bridge. The bridge is balanced for 50 Hz with $R_4 = 1000/\pi\ \Omega$ and C_4 = 300 nF. Calculate the dielectric loss angle? Sketch the loss angle by means of a phasor diagram.

d) Calculate the effective relative complex permittivity $\tilde{\varepsilon_r} = \varepsilon_r' + j\varepsilon_r''$ for the dielectric material. Explain the importance of the real and imaginary part of the complex permittivity and calculate the ratio of the conductive losses to the polarization losses.

e) Calculate the specific losses [mW/cm^3] of the dielectric material exposed to a 50 Hz alternating electric field stress with a peak value E = 11,34 kV/mm

Exercise 2 (High Voltage)

Danish Transmission system operator Energinet.dk is replacing major parts of the transmission network with PEX cables. All new installations are made with PEX cables. Such an example is the Anholt offshore wind farm connection at 220 kV (245 kV maximum). Such cables are frequently on-site HV tested after installation. According to IEC 60840 the test voltage should (for this voltage level) be 1,3 * maximum voltage between phase conductor and screen. The Anholt cable has a length of 55 km and a capacitance per phase C = 0,25 µF/km.

a) What will be the reactive power necessary to test one phase of the cable in its full length? Comment on the practical application of such level of reactive power for testing.

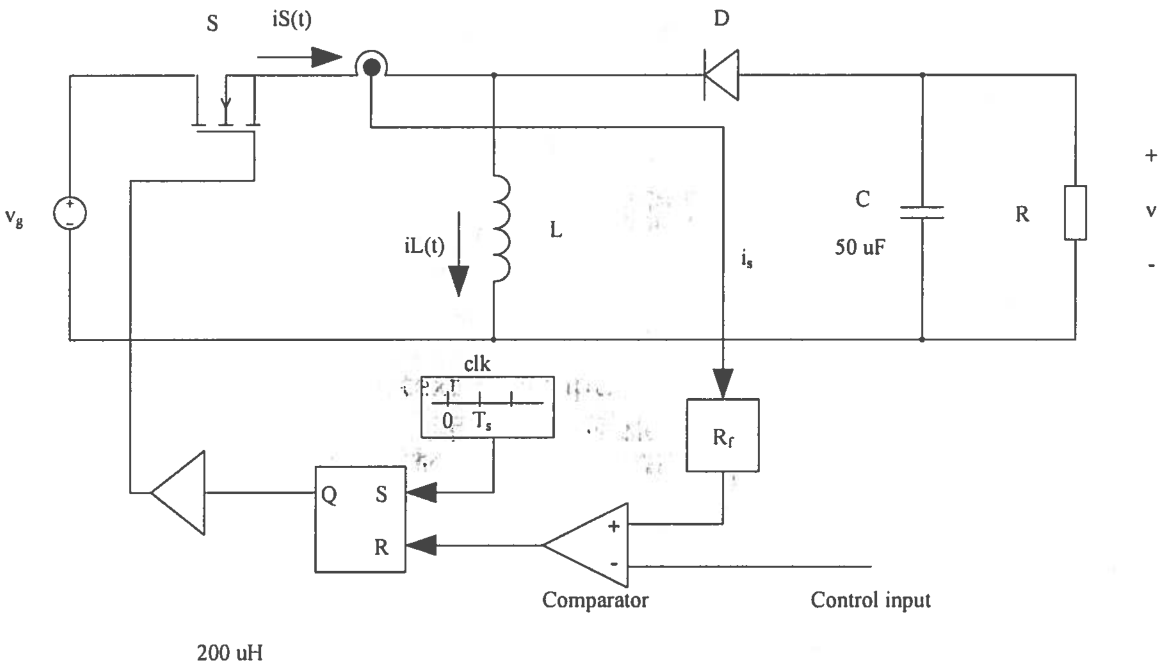
b) In order to test such large cables series resonant circuits are used. Test frequency can be in the range of 30 – 200 Hz for PEX cables. Draw a simple single line diagram of such test setup and calculate the inductance of the reactor for both 30 Hz and 200 Hz.

c) Assume a quality factor Q = 200 for the reactor and neglect losses in the cable. Calculate necessary supply voltage and current to supply the resonant test circuit for the two frequencies in b)

d) Select a test frequency (30 Hz or 200 Hz). Justify your answer!

Exercise 3 (Design of Switch Mode Converters)

Current Programmed Control of Buck-Boost converter



T_s = 10 μs R= 20 Ω V_g = 20 V V = -100 V R_f = 1 Ω L= 200μH

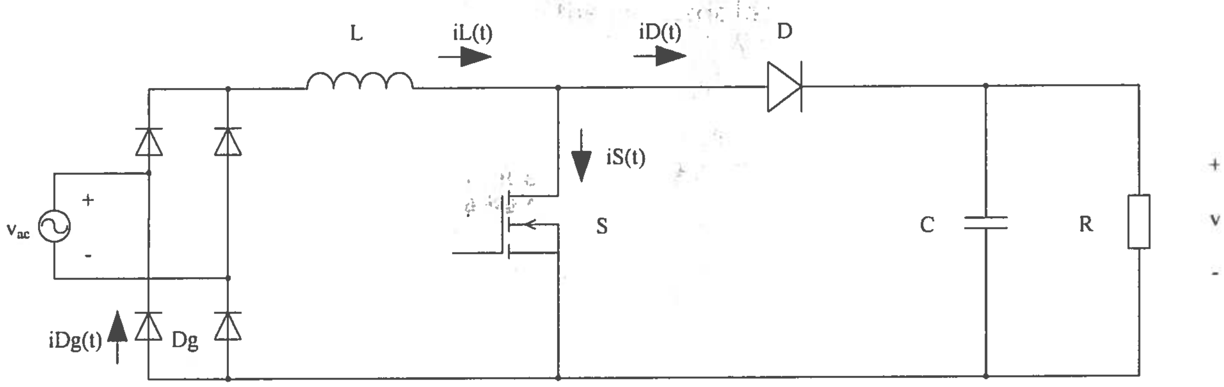
Assume ideal components (=> no power loss in power conversion)

a) Calculate the steady state average current value of the switch S.

b) Calculate the slopes m1 and m2.

Exercise 4 (Design of Switch Mode Converters)

Design a boost converter,



Specification:

Output voltage	390 V
Output power	500 W
Rms input voltage	230 V
Efficiency	1.0
Fundamental frequency	50 Hz
Switching frequency	100 kHz

In question a, b, c and e assume the converter operate in CCM and switching frequency ripple current in L is very small – so small you may ignore it.

a) For one fundamental period sketch the current of iDg(t) and $v_{ac}(t)$ label the axis

b) For one switching period sketch the current of iS(t) assume the average current is 1 A and the duty-cycle of S is 25 %. Label the axis

c) Calculate the RMS value of the inductor current iL(t).

d) For what values of L is the converter operating in CCM?

e) Sketch the waveform of the current in capacitor C. Label the axis.

Q# 1 ①

a) $C = \varepsilon \cdot \frac{A}{d} \Rightarrow \varepsilon = C \cdot \frac{d}{A}$

$\varepsilon = 43{,}8 \cdot 10^{-12} \cdot \frac{0.01}{\pi \cdot 0{,}05^{2}} = 5{,}578 \cdot 10^{-11}$

$\varepsilon = \varepsilon_r \cdot \varepsilon_0 \Rightarrow \varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \frac{5{,}578 \cdot 10^{-11}}{8{,}85 \cdot 10^{-12}} = \underline{\underline{6{,}30}}$

b) $s = 20\,mm \Rightarrow U = 59{,}0\,kV$

$R = U/I = 59000/12 \cdot 10^{-12} = 4{,}92 \cdot 10^{15}\ \Omega$

$R = \rho \frac{d}{A} \Rightarrow \rho = R\frac{A}{d} = 4{,}92 \cdot 10^{15} \frac{\pi \cdot 0{,}05^{2}}{0{,}01} =$

$3{,}86 \cdot 10^{15}$ $\rho = 3{,}86 \cdot 10^{15}\ \Omega$ $\sigma_0 = \frac{1}{\rho} = 1/3{,}86 \cdot 10^{15} = \underline{\underline{2{,}59^{-16}}}\ \frac{S}{m}$

c) (7.33) $\omega C_4 R_4 = \tan \delta_x$

$2\pi \cdot 50 \cdot 300 \cdot 10^{-9} \cdot 1000/\pi = 0{,}03 \rightarrow \underline{\delta_x = 1{,}72^\circ}$

d) $\tan \delta = \frac{\varepsilon_r'' + \sigma_0/\varepsilon_0 \cdot \omega}{\varepsilon_r'} \Rightarrow$

$\varepsilon_r' \cdot \tan\delta = \varepsilon_r'' + \sigma_0/\varepsilon_0\omega \Rightarrow \varepsilon_r'' = \varepsilon_r' \tan\delta - \sigma_0/\varepsilon_0\omega$

$\varepsilon_r'' = 6{,}3 \cdot 0{,}03 - \frac{2{,}59 \cdot 10^{-16}}{8{,}85 \cdot 10^{-12} \cdot 2\pi 50} = 0{,}189$

$\tilde{\underline{\varepsilon}}_r = \tilde{\varepsilon}_r' + j\,\tilde{\varepsilon}_r''$, where $\tilde{\varepsilon}_r'' = \varepsilon_r'' + \sigma_0/\varepsilon_0\omega$

$\tilde{\underline{\varepsilon}}_r = 6{,}30 + j\,(1{,}89 + 2{,}59 \cdot 10^{-16}/8{,}85 \cdot 10^{-12}\, 2\pi 50\,)$

SMALL CONDUCTIVE PART

$\underline{\tilde{\underline{\varepsilon}}_r \cong 6{,}30 + j\,1{,}89}$

CAPACITANCE

LOSSES (CONDUCTION POLARIZATION)

e)
$$P_{diel} = \omega C \tan\delta \, U^2$$
$$E = 8 \, kV/mm \Rightarrow U = 80 \, kV$$
$$P_{diel} = 2\pi 50 \cdot 438 \cdot 10^{-12} \cdot 0{,}03 \cdot 80000^2 = 2{,}64 W$$
$$P_{diel\,spec} = P_{diel}/V = 2{,}64 / \pi \cdot 5^2 \cdot 1 = \underline{\underline{33{,}6 \, mW/cm^3}}$$

Opg 2 Series Impedance reflected

(2)

a/ $X_C = 1/\omega C = 1/2\pi 50 \cdot 0{,}25 \cdot 10^{-6} \cdot 55 = 231{,}5\,\Omega$

$1{,}3 \cdot 245\,kV = 318\,kV$ test voltage.

$I = 318000/231{,}5 = 1376\,A$

$Q = I^2 \cdot X_C = 1376^2 \cdot 231{,}5 = \underline{438\ MW}$

Very high power, just like real power transformer, not practical for testing!

b/ Fig 2.20 p. 45

$\omega_0 = 1/\sqrt{LC} \Rightarrow L_0 = \dfrac{1}{\omega^2 C}$

$$L_{30Hz} = \frac{1}{(2\pi 30)^2 \cdot 0{,}25 \cdot 10^{-6} \cdot 55} = \underline{\underline{2{,}05\,H}}$$

$$L_{200Hz} = \underline{\underline{46\ mH}}$$

c/ $Q = \dfrac{\omega L}{R}$, $200 = \dfrac{2\pi \cdot 30 \cdot 2{,}05}{R}$

$R_{30Hz} = 1{,}93\,\Omega$, $R_{200Hz} = 0{,}290\,\Omega$

Resonance $\Rightarrow |V_C| = |V_L| = Q \cdot |V_s| \Rightarrow$

$318 = 200 \cdot |V_s| \Rightarrow |V_s| = \underline{1{,}59\,kV}$

$I_{30Hz} = \dfrac{V_s}{R_{30}} = \dfrac{1590}{1{,}93} = \underline{824\,A}$

$P_{30Hz} = I_{30}^2 \cdot R_{30} = 824^2 \cdot 1{,}93 = \underline{1{,}31\ MW}$

③

$$I_{200Hz} = \frac{V_s}{R_{200}} = \frac{1590}{0.290} = \underline{\underline{5494 A}}$$

$$P_{200Hz} = 5494^2 \cdot 0.290 = \underline{\underline{8.7 \text{ MW}}}$$

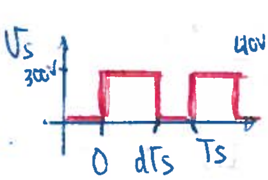
d/ See c/ We need 8.7 MW at 200 Hz but only 1.31 MW at 30 Hz

DESIGN OF SWITCH MODE CONVERTERS - lecture 1

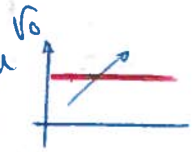
3/10/12

Example of single-phase converter:

Laptop/mobile charger → AC ~ 230V → DC voltage.



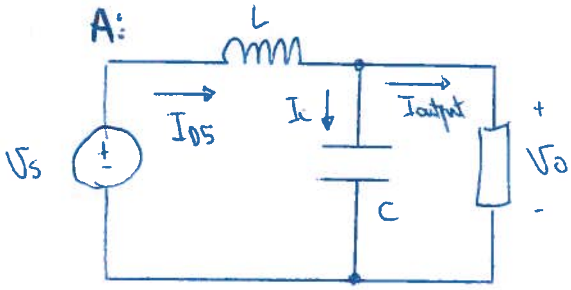
but computer wants to see



$\boxed{d = \frac{t_{ON}}{T_s}}$ $d = 0 \div 1$ DUTY CYCLE

Taking exercise 12.4:

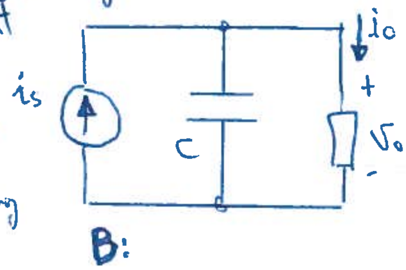
At the right of transformer:



2nd order system.

Thevenin circuit: voltage source + L → current source

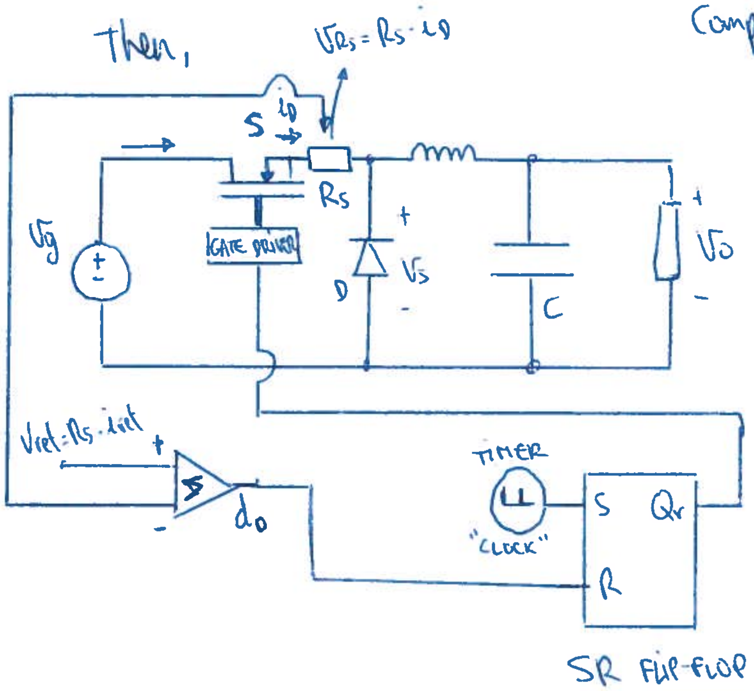
simplifying



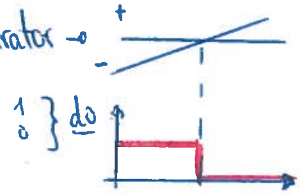
If the input current and the output current → the outvoltage goes UP!

But $i_s > i_o \rightarrow V_o > V_s$.

Then,

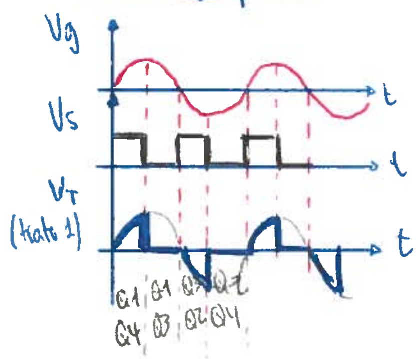


Comparator →

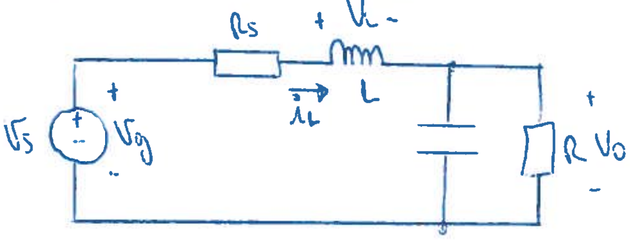


The function of C is to maintain the RIPPLE as constant as possible, and then the output will be also constant.

Eloy's graphic:

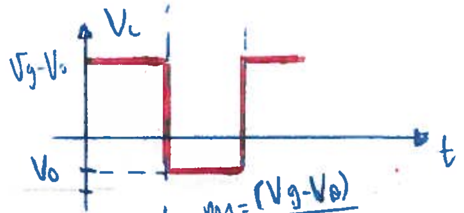


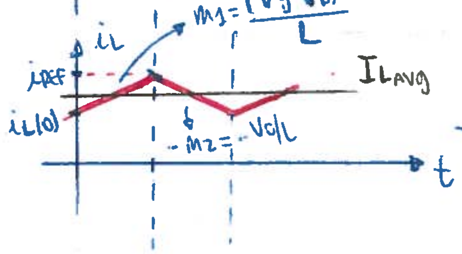
Equivalent for S=ON: | $V_s = V_g$



S=ON → $V_s = V_g$ S=OFF → $V_s = 0V$

CURRENT PROGAMMED CONTROL



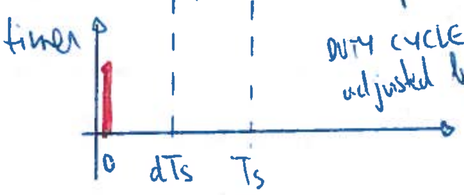


$$m_1 = \frac{(V_g - V_o)}{L}$$

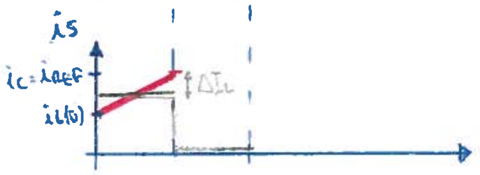
$$-m_2 = \frac{-V_o}{L}$$

$$i_L = \frac{V_g - V_o}{L} \cdot t + i_L(0)$$

When my i_L (inductor current) reaches my i_{ref}, it sleeps.



DUTY CYCLE will be adjusted by the timer.

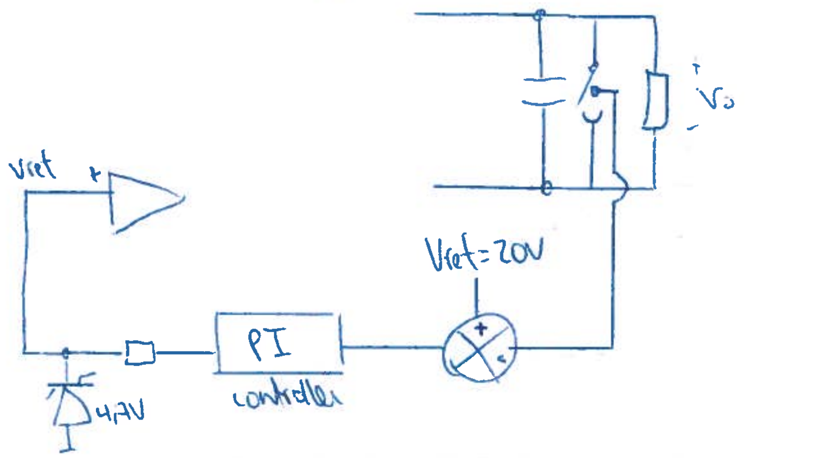


$\Delta I_L \sim$ SMALL

We do a simple assumption, from the thevenin simplification

$$i_s \sim i_{REF} = i_c$$

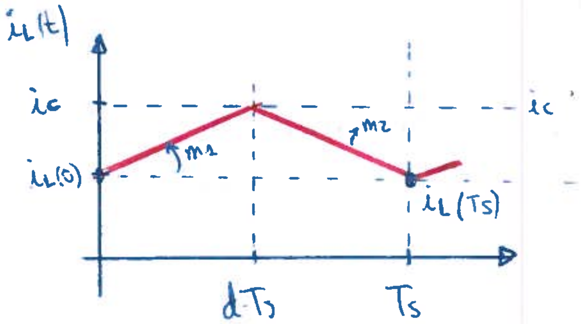
In a real situation, we will measure OUTPUT VOLTAGE V_o and compare to V_{ref} and send again to the comparator ▷ through a PI controller.



DESIGN OF SWITCH MODE CONVERTERS - lecture 1

3/10/1

PEAK CURRENT CONTROL:



Give unstable operation if $d > 0{,}5$.

↳ The signal will become distorted!

① $i_c = m_1 \cdot dT_s + i_L(0)$ / ② $i_L(T_s) = i_c - m_2 \cdot (1-d) \cdot T_s$

2 equations describing how the current changes.

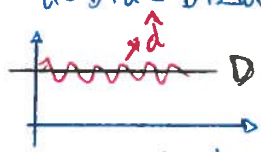
From here, we can do a SMALL SIGNAL MODEL.

- $i_c = m_1 \cdot d \cdot T_s + i_L(0)$ $\quad i_L(T_s) = i_c - m_2 \cdot (1-d) \cdot T_s$
- $d = D + \hat{d}$ $\quad i_L(0) = I_L(0) + \hat{i}_L(0)$ $\quad i_L(T_s) = I_L(T_s) + \hat{i}_L(T_s)$

CAPITAL LETTERS: constant

Ex.

$d = D + \hat{d} \equiv D + \Delta d$



we say that duty cycle is a function of t

D: constant $\hat{d}$: variation

i_c = constant (I_c), m_1, m_2 and T_s are also constants.

Then,

$i_c = m_1 \cdot (D + \hat{d}) \cdot T_s + (I_L(0) + \hat{i}_L(0))$ $\quad I_L(T_s) + \hat{i}_L(T_s) = i_c - m_2 \cdot (1 - D - \hat{d}) \cdot T_s$

SMALL SIGNALS:

Constants: are taken out

$0 = m \cdot \hat{d} \cdot T_s + \hat{i}_L(0)$

$\boxed{\hat{i}_L(0) = -m_1 \hat{d} \cdot T_s}$

$\hat{i}_L(T_s) = -m_2 \cdot (-\hat{d}) \cdot T_s \longrightarrow \boxed{\hat{i}_L(T_s) = m_2 \cdot \hat{d} \cdot T_s}$

$\hat{i}_L(T_s) = m_2 \left(- \dfrac{\hat{i}_L(0)}{m_1} \right) \longrightarrow \boxed{\hat{i}_L(T_s) = -\dfrac{m_2}{m_1} \cdot \hat{i}_L(0)}$

The ratio between $m_2/m_1 < 1$.

Unstable operation: $\dfrac{m_2}{m_1} > 1$

From the initial circuit (current programmed control):

$m_2 = \dfrac{V_o}{L}$

$m_1 = \dfrac{V_g - V_o}{L}$

$V_o = V_g \cdot d$

$\dfrac{m_2}{m_1} = \dfrac{V_o}{L} \cdot \dfrac{L}{V_g - V_o}$

$\dfrac{m_2}{m_1} = \dfrac{V_o}{V_g - V_o} \longrightarrow \dfrac{m_2}{m_1} = \dfrac{V_g \cdot d}{V_g - V_g \cdot d} = \dfrac{d}{1-d}$

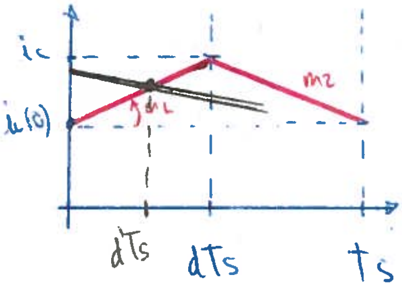
Then,

$\dfrac{d}{1-d} > 1$

$d > 1 - d$

$2d > 1 \longrightarrow \boxed{d > \dfrac{1}{2}}$

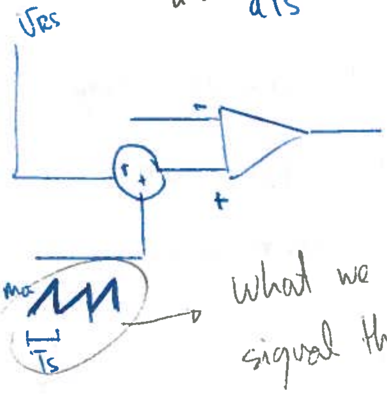
For the slope, if we choose $m_a = 0{,}5 \cdot m_2$ (where m_a is the slope of the new signal)



$m_a = 0{,}5 \cdot m_2$ STABLE! (from 0 to 100% duty

$m_a = m_2$

m_a is the slope of the "correction signal" (compensation)



what we get is a compensation signal that reduces the duty cycle ($d < 0{,}5$)