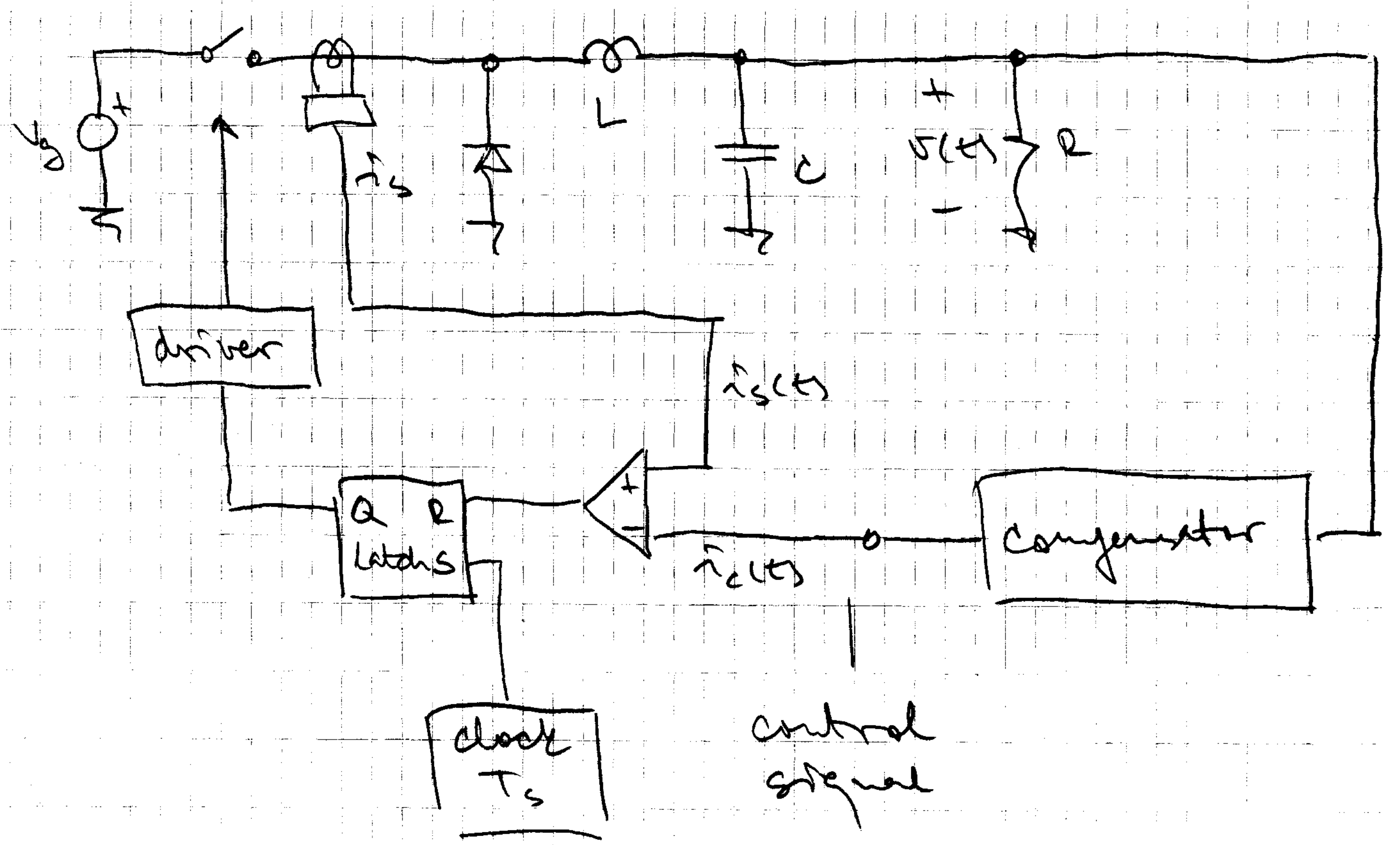
*

Техника струјног програмирања

- до сада - duty ratio programmed mode
  $v(t)$ је контролисано са $D(t)$

- у задње време (10 година) "current-programmed" mode, излаз је контролисан избором праве вредности струје транзистора (peak transistor current) peak ($i_s(t) \cong i_c(t)$).

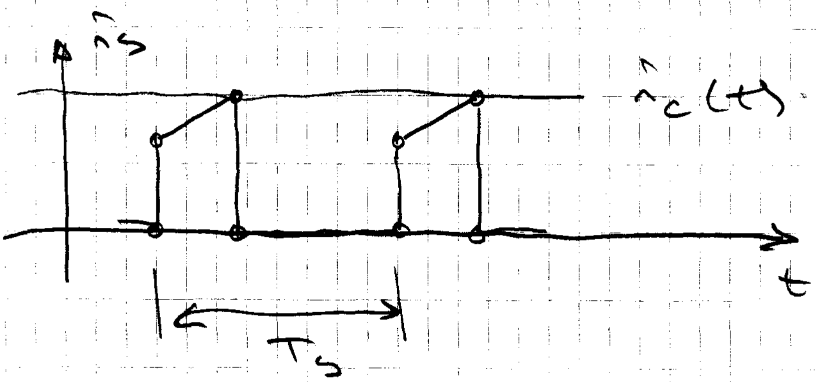
- Пример: buck converter



- две петље регулације, мерења је регулација

- D(t) није директно контролисано

- лако једна компонента



Предности / мане технике струјног програмирања

1° dynamics is potentially simpler
$\frac{\hat{v}}{\hat{i}_c}$ има један пол мање од $\frac{\hat{v}}{\hat{d}}$.
Реално постоји и други пол, али на знатно вишим учестаностима од PWM случаја

2° Прекострујна заштита потребна сама по себи, транзистор се гаси кад треба

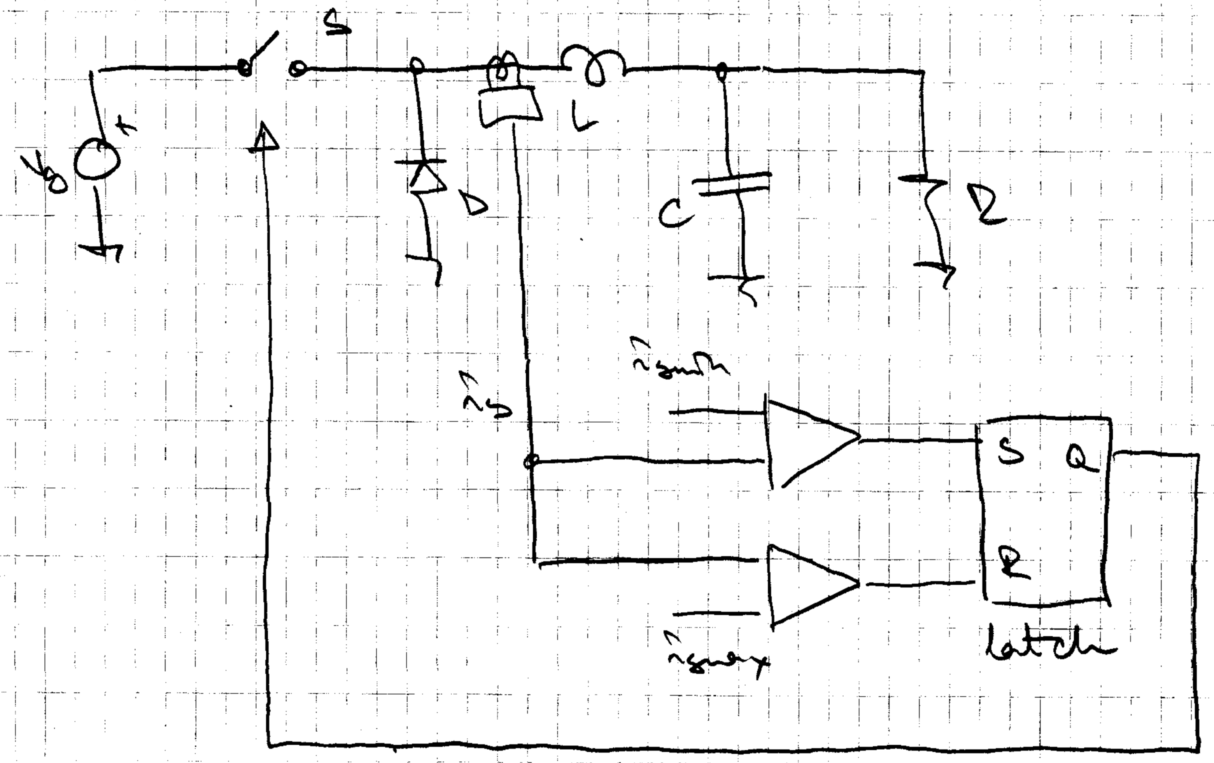
3° Много лакше паралелисање, open loop може директно, ако би имали исто то може и closed loop.

4. Кај push-pull-а и кај full-bridge-а нема проблема са заситеним језгром

Мане:

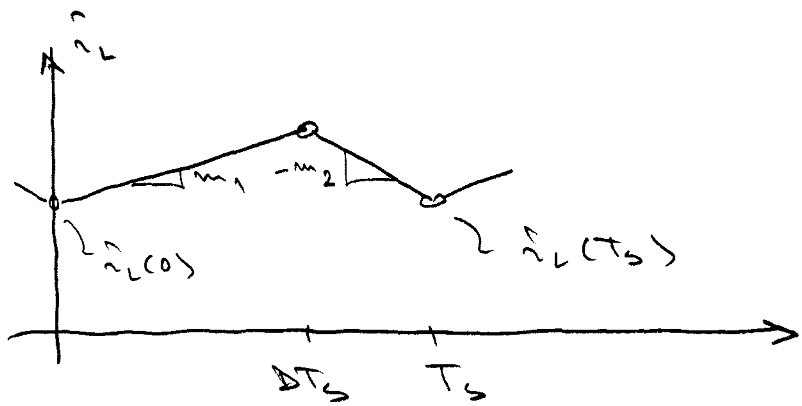
1. За steady-state $D > 0.5$ динамика нема $\hat{i}$ нестабилна. Објашњава се додатком "artificial ramp" на i_s. Биће објашњено

Историјска напомена:



- нема проблема стабилности
- f_s није константно
- компликовано
- ... не ... и не ...
- континуално мерење i_c → $i_c + \Delta i = i_{max}$
  → $i_c - \Delta i = i_{min}$
  → ... 0!

Discrete-Time Analysis of Basic Current-Mode Converter



$$m_1 = \frac{d\hat{i}_L}{dt} \quad : \ 1^{st} \text{ interval}$$

$$-m_2 = \frac{d\hat{i}_L}{dt} \quad : \ 2^{nd} \text{ interval}$$

	m_1	m_2
buck	$\frac{V_g - V}{L}$	V/L
boost	V_g/L	$(V - V_g)/L$
buck-boost	V_g/L	$-V/L$

$$\hat{i}_L(DT_s) = \hat{i}_c = \hat{i}_L(0) + m_1 DT_s$$

$$D = \frac{\hat{i}_c - \hat{i}_L(0)}{m_1 T_s}$$

2nd interval

$$\hat{i}_L(T_s) = \hat{i}_L(DT_s) - D'T_s m_2 =$$

$$= \hat{i}_L(0) + m_1 DT_s - m_2 D'T_s \qquad (*)$$

steady-state

$$\hat{i}_L(0) = \hat{i}_L(T_s)$$

$$0 = m_1 D - m_2 D' \qquad (**)$$

Consider small perturbation in $\hat{i}_L(0)$:

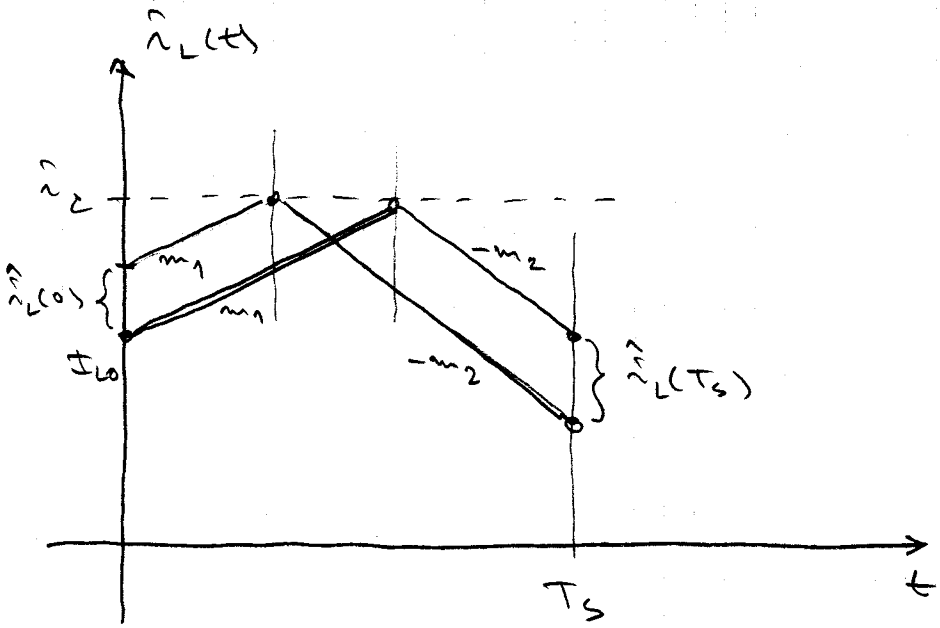
$$\hat{i}_L(0) = I_{L0} + \hat{\hat{i}}_L(0)$$

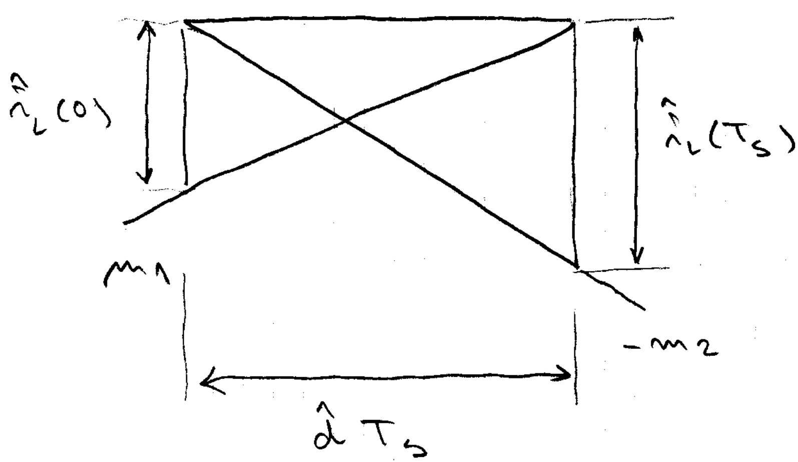
I_{L0} је steady-state $\hat{i}_L(0)$ које задовољава једначину (*)

Претпоставка $|\hat{\hat{i}}_L(0)| \ll |I_{L0}|$, хоћу да видим да ли се п расте или опада

нестабилно стабилно

Занима ме $\hat{\hat{i}}_L(nT_s)$





$\hat{d} < 0$

$\hat{i}_L(0) > 0$

$\hat{i}_L(T_s) < 0$

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

$$-\hat{i}_L(T_s) = -m_2 \hat{d}\, T_s$$

eliminate $\hat{d}\, T_s$

$$-\frac{\hat{i}_L(0)}{m_1} = \frac{\hat{i}_L(T_s)}{m_2}$$

$$\hat{i}_L(T_s) = \hat{i}_L(0)\left(-\frac{m_2}{m_1}\right)$$

$$\frac{m_2}{m_1} = \frac{D}{D'} \qquad (**)$$

$$\hat{i}_L(T_s) = \hat{i}_L(0)\left(-\frac{D}{D'}\right)$$

$$\boxed{\hat{i}_L(nT_s) = \hat{i}_L(0)\left(-\frac{D}{D'}\right)^n}$$

за стабилност

$$\frac{D}{D'} < 1 \qquad \frac{D}{1-D} < 1$$

$$D < 1 - D \qquad 2D < 1$$

$$\boxed{D < \frac{1}{2}}$$ - стабилно

- Два примера из Бобове књиге

Example Operation of boost converter with $V_g = 20$, $V = 50$

note $\frac{V}{V_g} = \frac{1}{D'} \Rightarrow D' = \frac{2}{5} \Rightarrow D = \frac{3}{5} > \frac{1}{2}$

so the current programmed mode should be unstable.

$$\left(-\frac{D}{D'}\right) = \left(-\frac{3/5}{2/5}\right) = -1.5$$

n	$\hat{i}(nT_s) = \hat{i}(0)\left(-\frac{D}{D'}\right)^n$
0	$\hat{i}(0)$
1	$-1.5\,\hat{i}(0)$
2	$+2.25\,\hat{i}(0)$
3	$-3.375\,\hat{i}(0)$

etc.

– growing oscillation

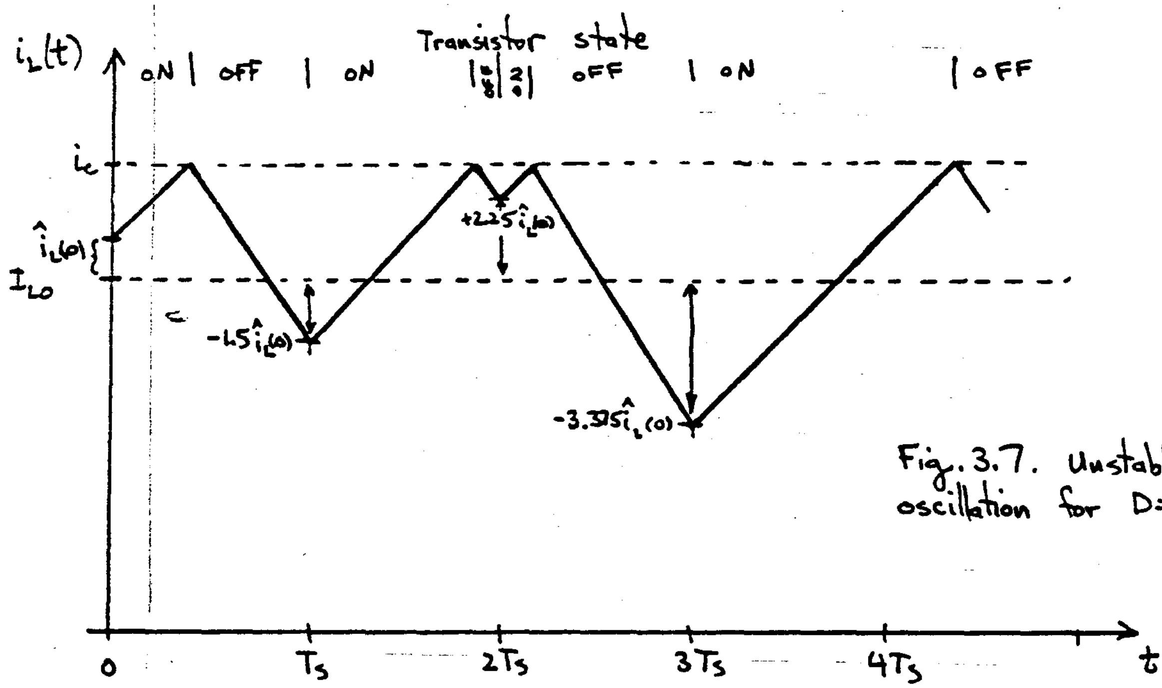


Fig. 3.7. Unstable oscillation for D=0.6

It can be seen from Fig. 3.7 that the oscillations grow in amplitude, and the current-mode controller does not operate correctly. However, once the oscillations become large, they no longer grow without bound. Instead, the inherent nonlinearity (saturation) of the system limits the maximum amplitude of the oscillations.

For $V_g = 20$, $V = 30$:

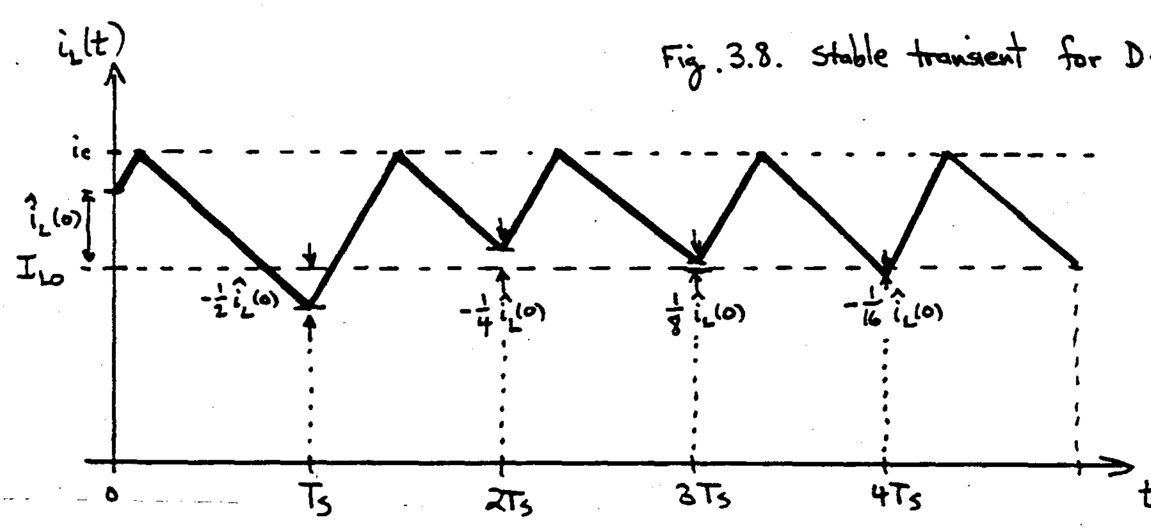
then $D' = \frac{1}{3}$, $-\frac{D}{D'} = -\frac{1}{2}$

n	$\hat{i}(nT_s) = \hat{i}(0)\left(-\frac{D}{D'}\right)^n$
0	$\hat{i}(0)$
1	$-\frac{1}{2}\,\hat{i}(0)$
2	$\frac{1}{4}\,\hat{i}(0)$
3	$-\frac{1}{8}\,\hat{i}(0)$

etc.

disturbance becomes small after a few intervals

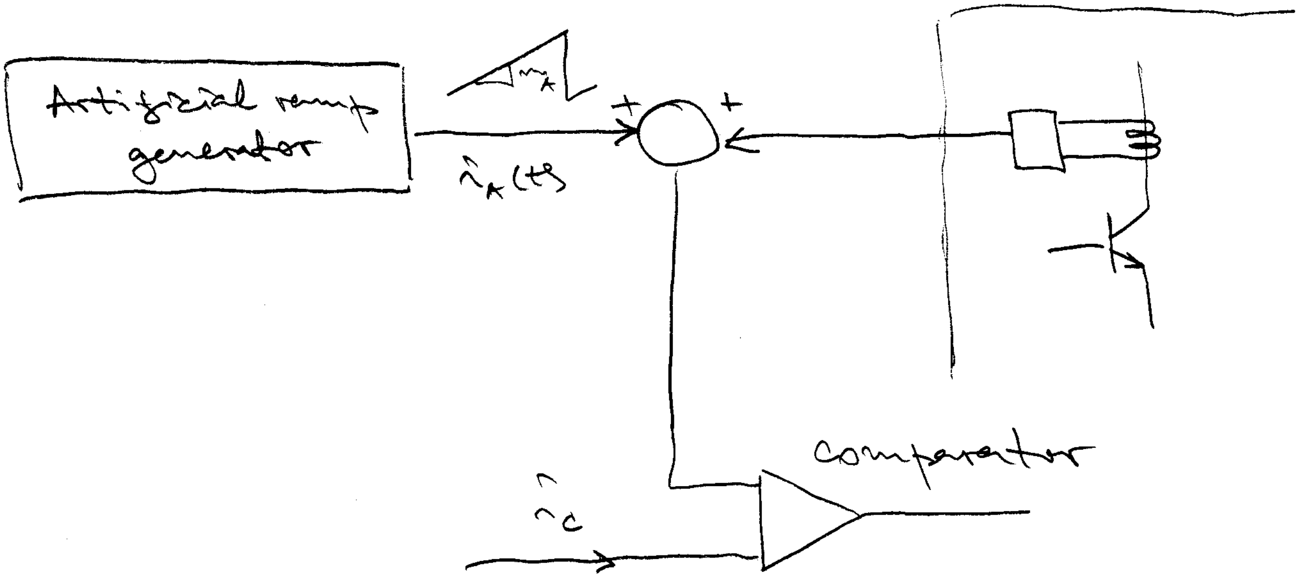
Fig. 3.8. Stable transient for $D = \frac{1}{3}$

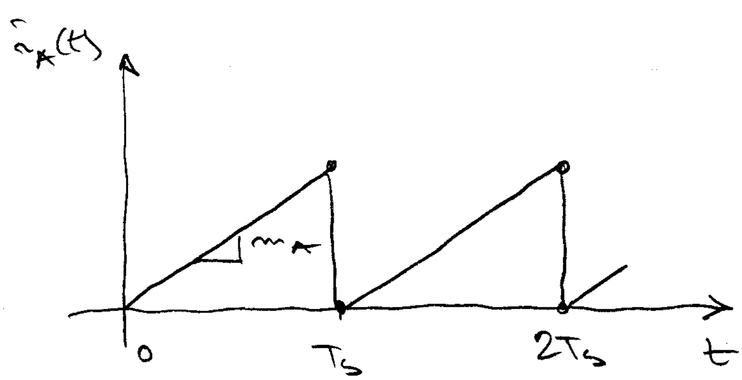


Нестабилност за $D > \frac{1}{2}$ не зависи од converter topology.

Artificial Ramp

commonly-used solution, додаје се artificial ramp на мерену струју прекидача





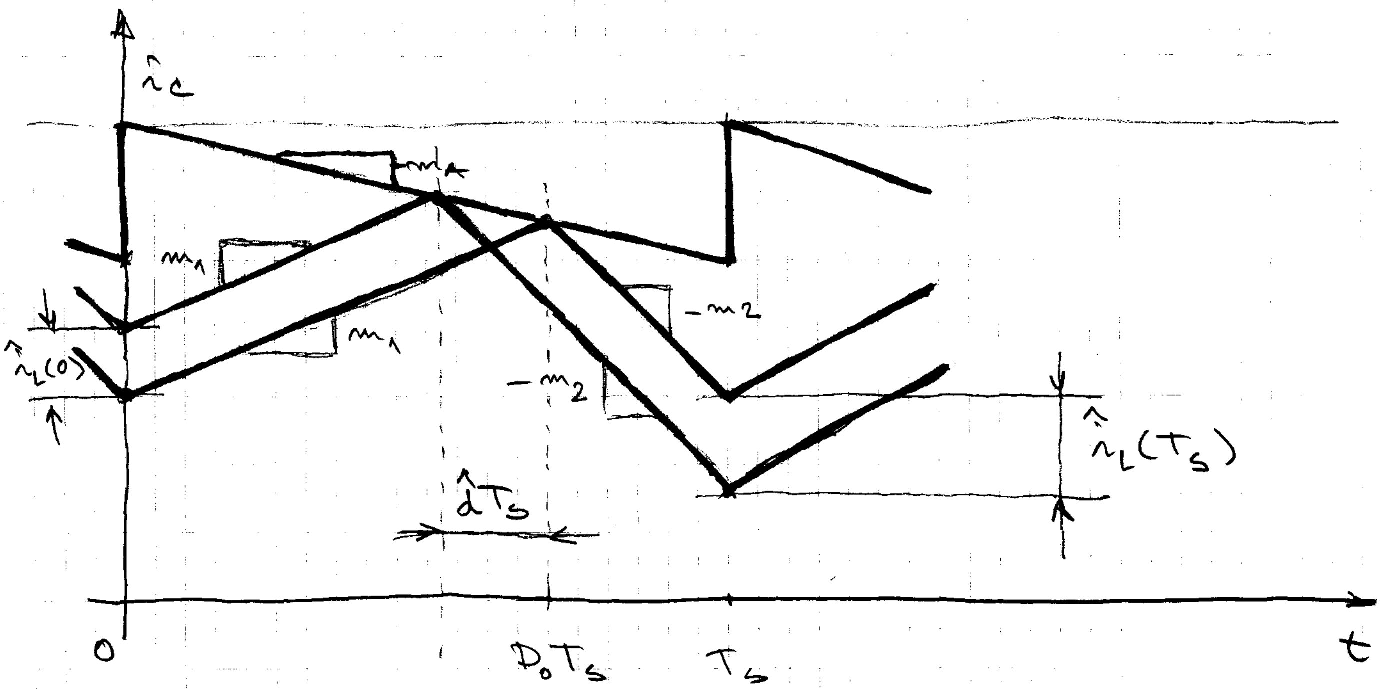
Транзистор се пали када

$$\hat{i}_A(t) + \hat{i}_L(t) = \hat{i}_c$$

односно

$$\hat{i}_L(t) = \hat{i}_c - \hat{i}_A(t)$$

важи само у тренутку када се транзистор пали



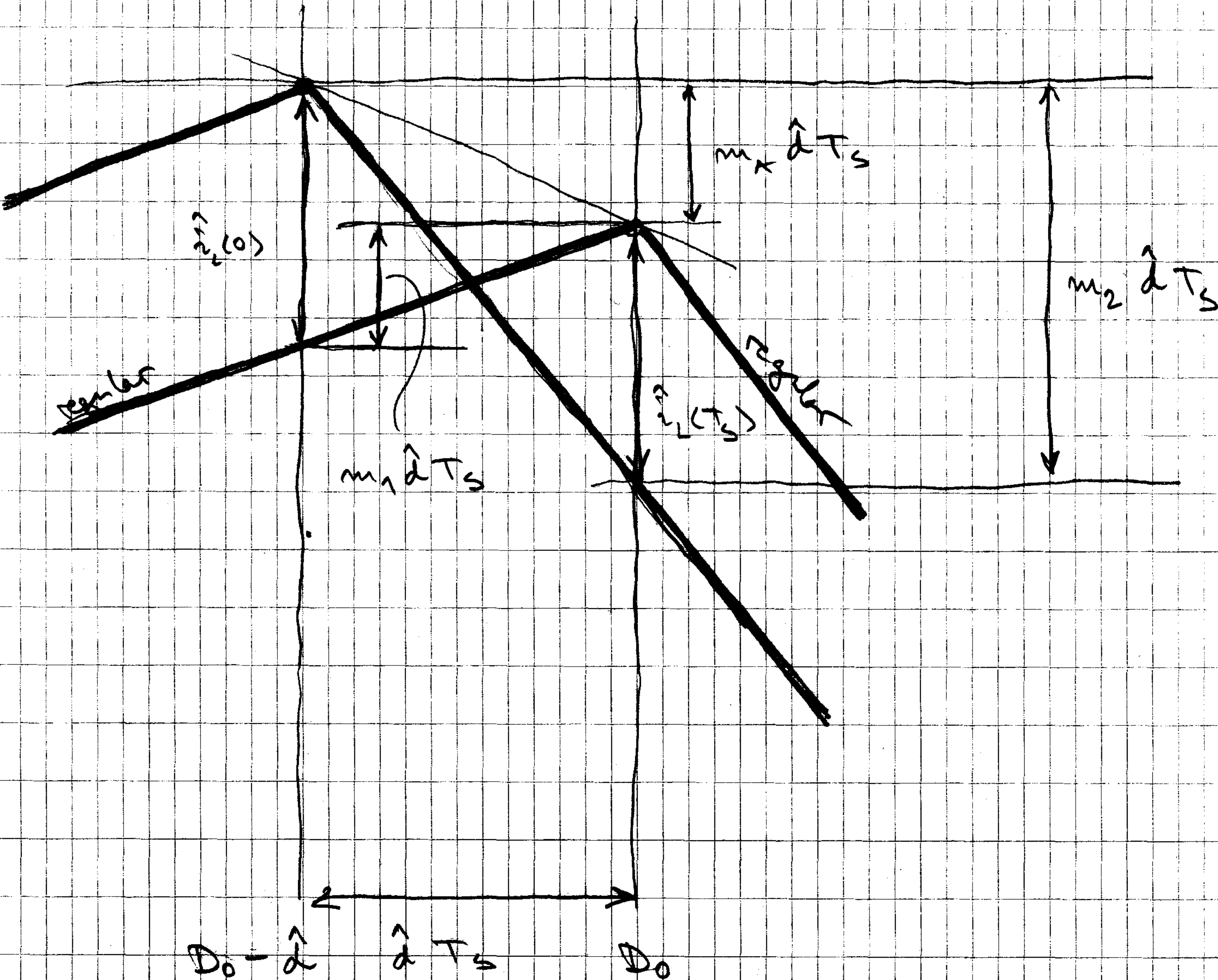
$$-\hat{i}_L(0) = \hat{d}\,T_s\,m_1 - \hat{d}\,T_s(-m_A) =$$

$$= \hat{d}\,T_s(m_1 + m_A)$$

$$-\hat{i}_L(T_s) = -m_2\,\hat{d}\,T_s - \hat{d}\,T_s(-m_A) =$$

$$= \hat{d}\,T_s(m_A - m_2)$$

погледај! →



$$\hat{i}_L(0) = m_A \hat{d} T_s + m_1 \hat{d} T_s = (m_1 + m_A)\hat{d} T_s$$

$$\hat{i}_L(T_s) = -m_2 \hat{d} T_s + m_A \hat{d} T_s = (m_A - m_2)\hat{d} T_s$$

$$\frac{\hat{i}_L(T_s)}{\hat{i}_L(0)} = \frac{m_A - m_2}{m_1 + m_A}$$

$$\frac{\hat{i}_L(T_s)}{\hat{i}_L(0)} = \left(-\frac{m_2 - m_A}{m_1 + m_A}\right)$$

$$\boxed{\hat{i}_L(nT_s) = \left(-\frac{m_2 - m_A}{m_1 + m_A}\right)^n \hat{i}_L(0)}$$

$m_A = 0$ – [illegible] [illegible] [illegible]

$\hat{i}_L \to \infty$ ако $\left|\frac{m_2 - m_A}{m_1 + m_A}\right| > 1$

$\hat{i}_L \to 0$ ако $\left|\frac{m_2 - m_A}{m_1 + m_A}\right| < 1$

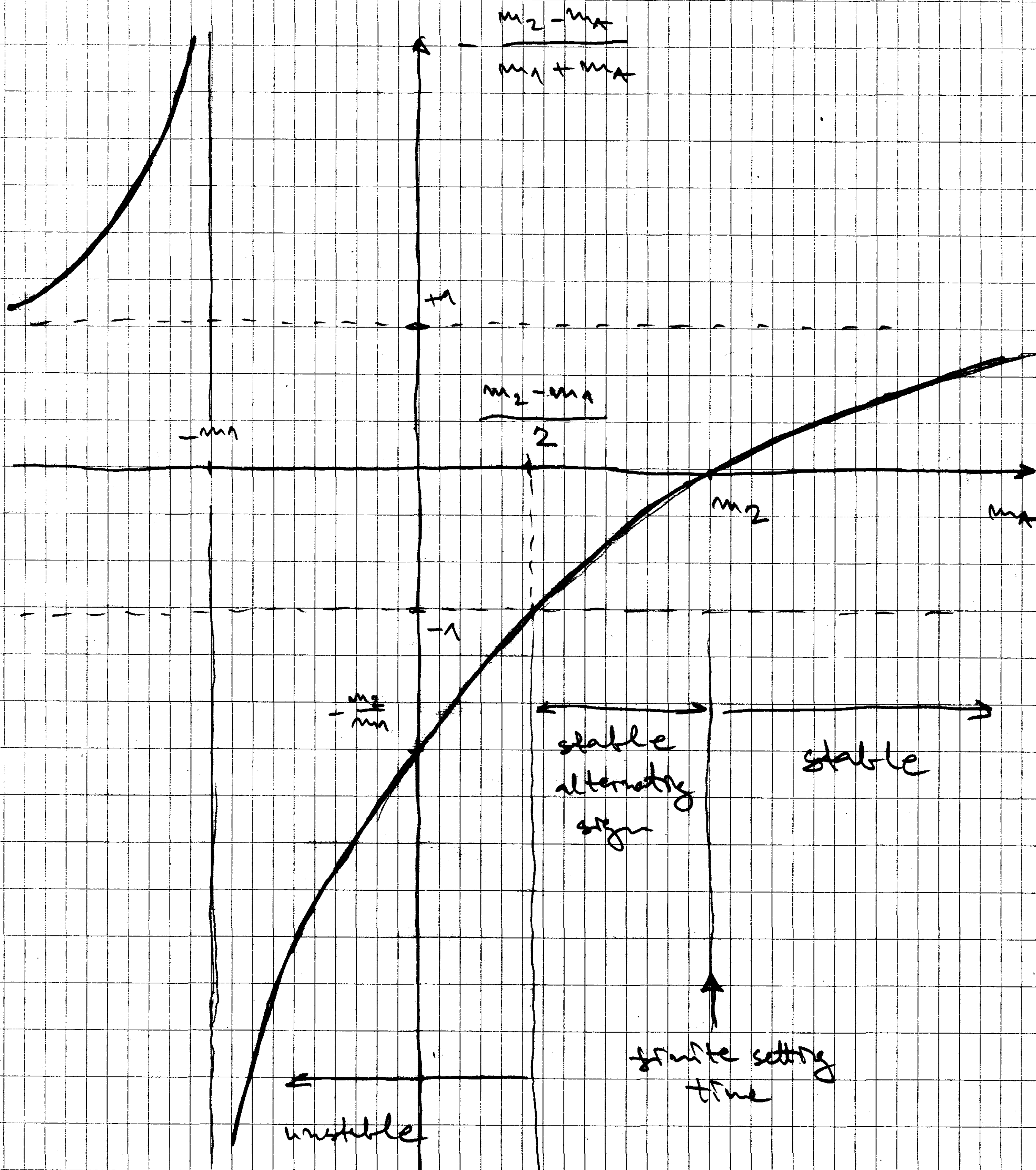
[illegible]: $-\frac{m_2 - m_A}{m_1 + m_A} \quad (m_A)$

[illegible]

$D_0 > \frac{1}{2} \qquad m_2 > m_1$

$D_0 < \frac{1}{2} \qquad m_1 > m_2$.

$D_0 > \frac{1}{2}$, $m_2 > m_1$



$m_1 > m_2$ — stable

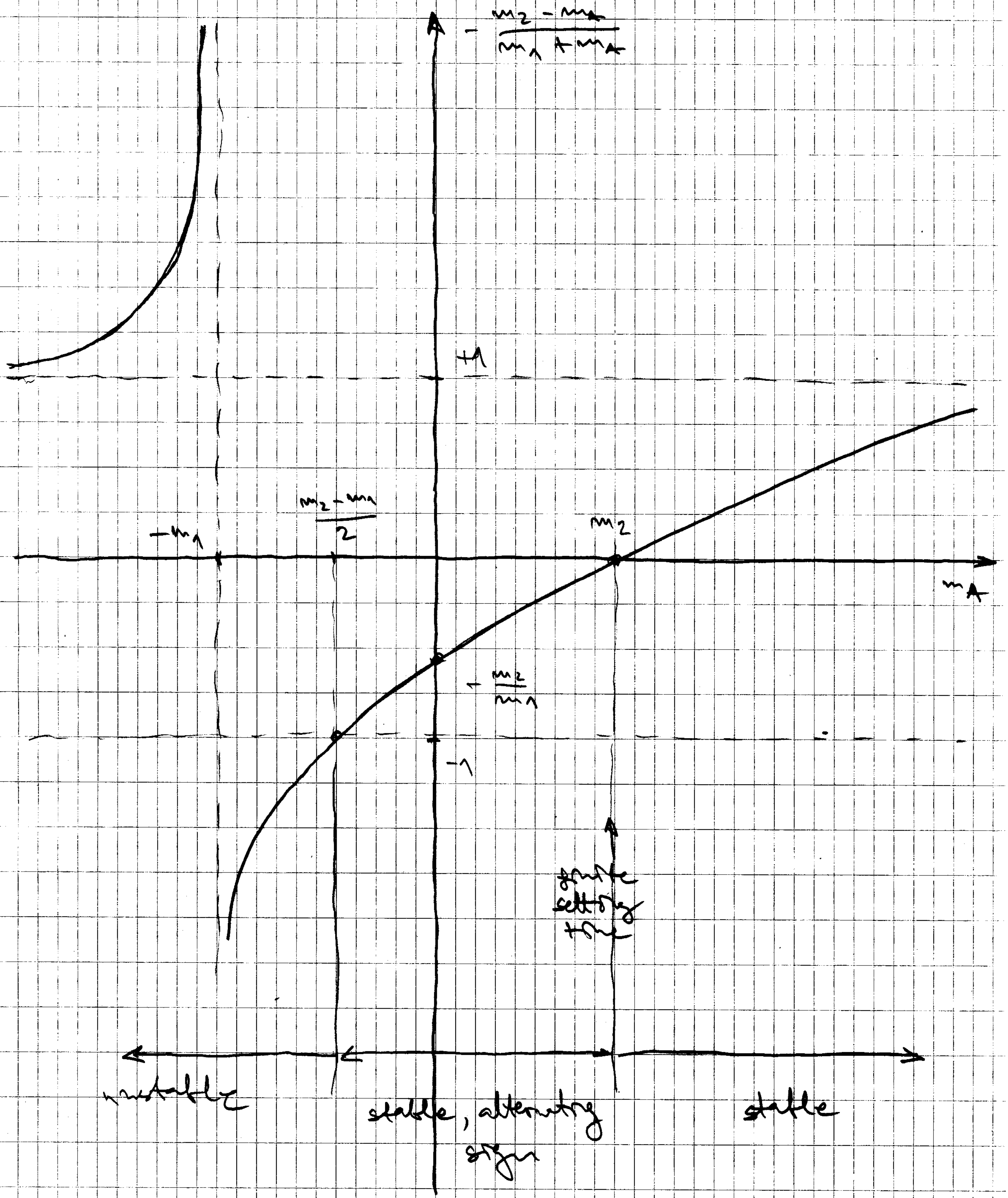
$\frac{m_2 - m_1}{2} < m_1 < m_2$ — stable, alternating sign

$m_1 < \frac{m_2 - m_1}{2}$ — unstable

unde este m_1 nu rămâne $\hat{\imath}_c$ nu mai este ca $\bar{\hat{\imath}}_L$, nu e mare

$m_1 = m_2$ — finite settling time

$D_0 < \frac{1}{2}$, $m_2 < m_1$



$m_1 > m_2$ - stable

$m_2 > m_1 > \frac{m_2 - m_1}{2}$ - stable, alternating sign

$m_1 = m_2$ - finite setting time

$m_1 < \frac{m_2 - m_1}{2}$ - unstable

finite setting time?

m_2 се мења са D_0, тј. са

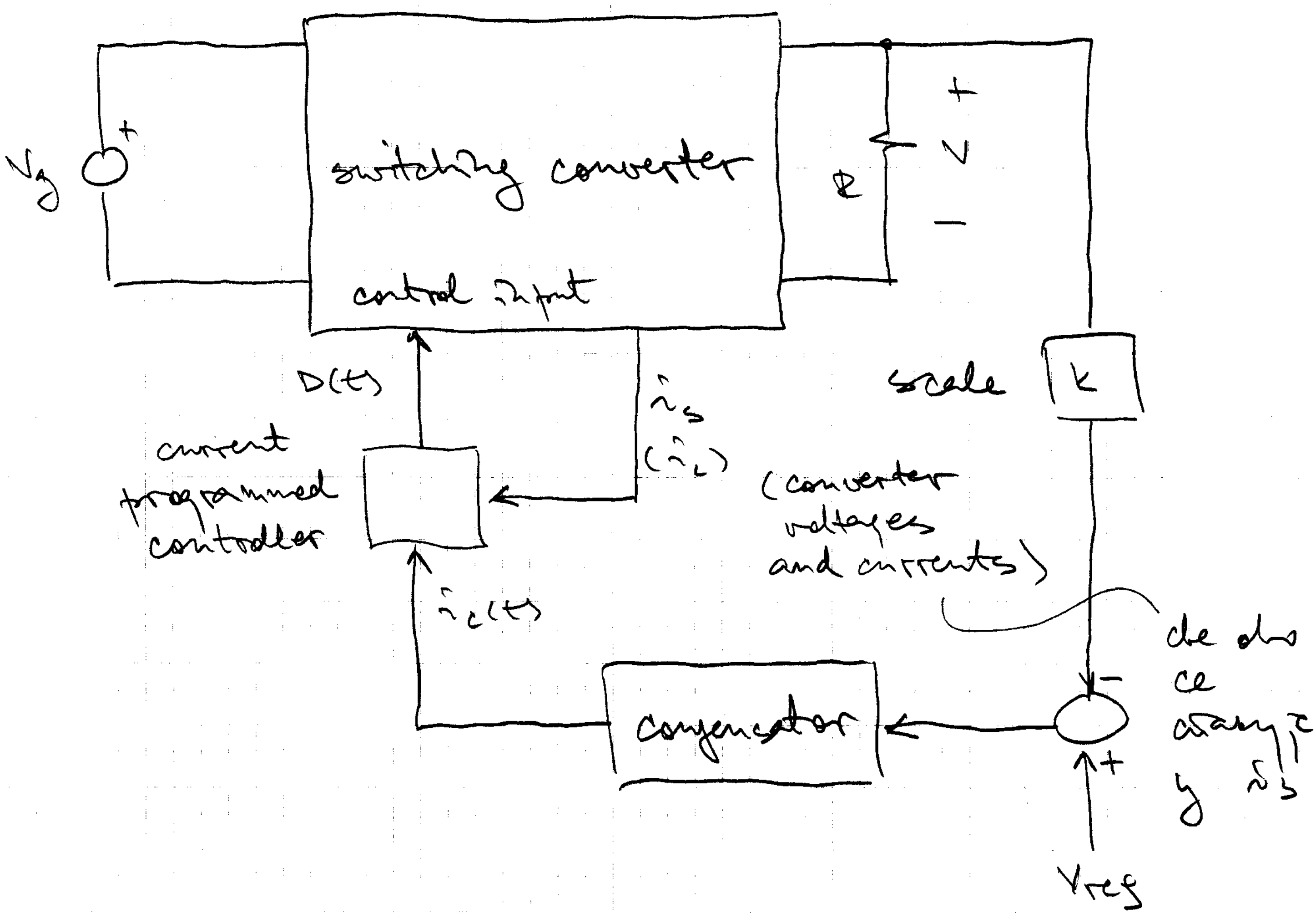
променом појачања. Не може

се направити finite setting time кад

појачање [illegible] [illegible]

Регулација претварача са струјним програмирањем

- дупла петља регулације



- equivalent circuit, small signal model,

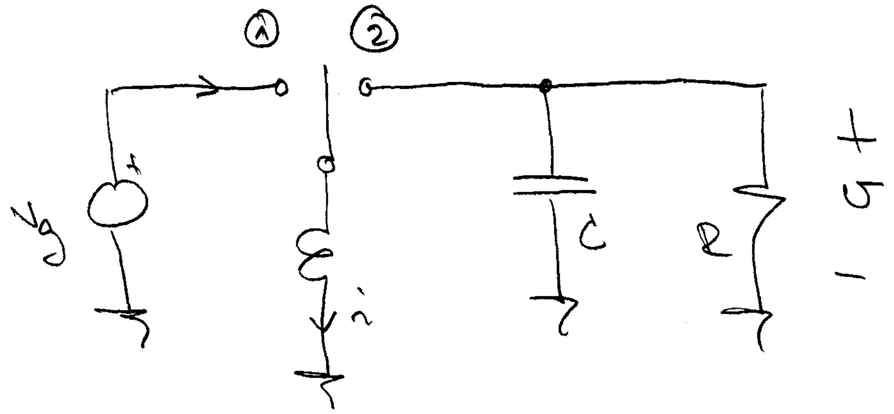
$\cancel{\hat{d}}$ $\hat{i}_c$

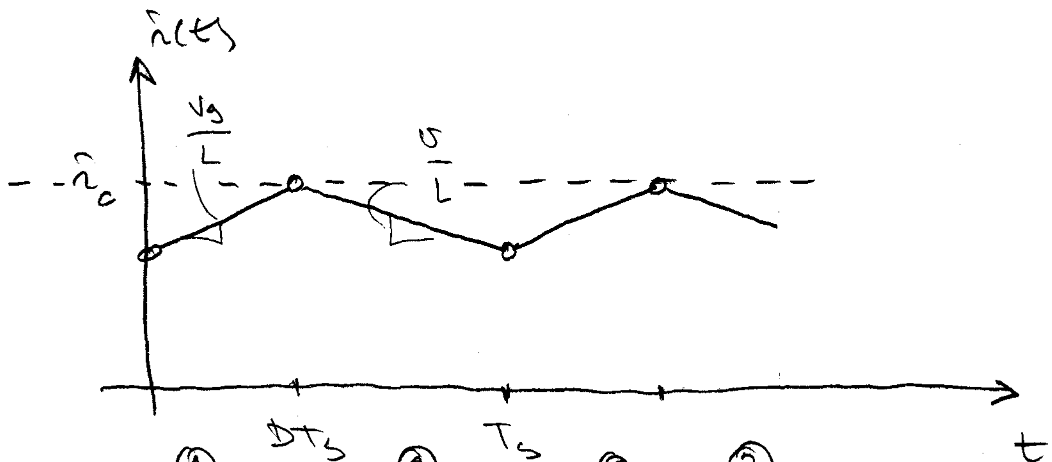
$\hat{i}_L \cong \hat{i}_C$ — ово уклања пол — [illegible]

- реално постоји пол ~~на~~ на високим учестаностима

- опет state-space averaging

Simplified Equivalent Circuit Modelling, Buck-~~Boost~~ Example





State-Space Equations

$$L\frac{d\hat{i}}{dt} = D_0'\hat{v} + D_0\hat{v}_g + (V_g - V_0)\hat{d}$$

$$C\frac{d\hat{v}}{dt} = -D_0'\hat{i} - \frac{\hat{v}}{R} + I_0\hat{d}$$

$$\hat{i}_g = D_0\hat{i} + I_0\hat{d}$$

Laplace transform

$$sL\hat{i}(s) = D_0'\hat{v}(s) + D_0\hat{v}_g(s) + (V_g - V_0)\hat{d}(s)$$

$$sC\hat{v}(s) = -D_0'\hat{i}(s) - \frac{\hat{v}(s)}{R} + I_0\hat{d}(s)$$

$$\hat{i}_g(s) = D_0\hat{i}(s) + I_0\hat{d}(s)$$

converter is stable, ripple is small, artificial ramp is not too large

$$\hat{i}_c(s) \cong \hat{i}(s)$$

$$sL\hat{i}_c(s) \cong D_0'\hat{v}(s) + D_0\hat{v}_g(s) + (V_g - V_0)\hat{d}(s)$$

$$\hat{d} = \frac{sL\hat{i}_c(s) - D_0'\hat{v}(s) - D_0\hat{v}_g(s)}{V_g - V_0}$$

– циљ: елиминисати $\hat{d}(s)$ и заменити са $\hat{i}_c(s)$

$$sC\hat{v}(s) = -D_0'\hat{i}_c(s) - \frac{\hat{v}(s)}{R} + I_0\frac{sL\hat{i}_c(s) - D_0'\hat{v}(s) - D_0\hat{v}_g(s)}{V_g - V_0}$$

$$\hat{i}_g(s) = D_0\hat{i}_c(s) + I_0\frac{sL\hat{i}_c(s) - D_0'\hat{v}(s) - D_0\hat{v}_g(s)}{V_g - V_0}$$

– сређимо и групишемо чланове

$$sC\hat{v}(s) = \left(\frac{sLI_0}{V_g - V_0} - D_0'\right)\hat{i}_c(s) -$$

$$- \left(\frac{D_0'I_0}{V_g - V_0} + \frac{1}{R}\right)\hat{v}(s) - \left(\frac{D_0I_0}{V_g - V_0}\right)\hat{v}_g(s)$$

$$\hat{i}_g(s) = \left(D_0 + \frac{sLI_0}{V_g - V_0}\right)\hat{i}_c(s) -$$

$$- \left(\frac{D_0'I_0}{V_g - V_0}\right)\hat{v} - \left(\frac{D_0I_0}{V_g - V_0}\right)\hat{v}_g(s)$$

убацимо steady-state equations

$$V_0 = -\frac{D_0}{D_0'}V_g \ ; \quad I_0 = -\frac{V_0}{D_0'R} \rightarrow \frac{D_0V_g}{D_0'^2R}$$

$$\frac{I_0}{V_g - V_0} = \frac{D_0 V_g}{D_0'^2 R \left(V_g + \frac{D_0}{D_0'} V_g\right)} = \frac{D_0}{D_0' R}$$

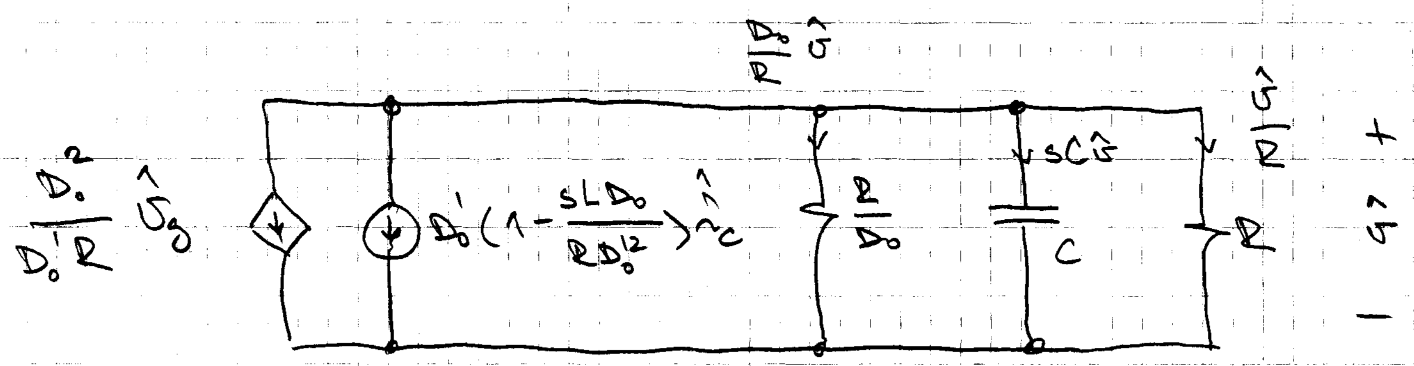
па је:

$$sC\hat{v} = \left(\frac{sLD_0}{D_0' R} - D_0'\right)\hat{i}_c - \left(\frac{D_0}{R} + \frac{1}{R}\right)\hat{v} - \left(\frac{D_0^2}{D_0' R}\right)\hat{v}_g$$

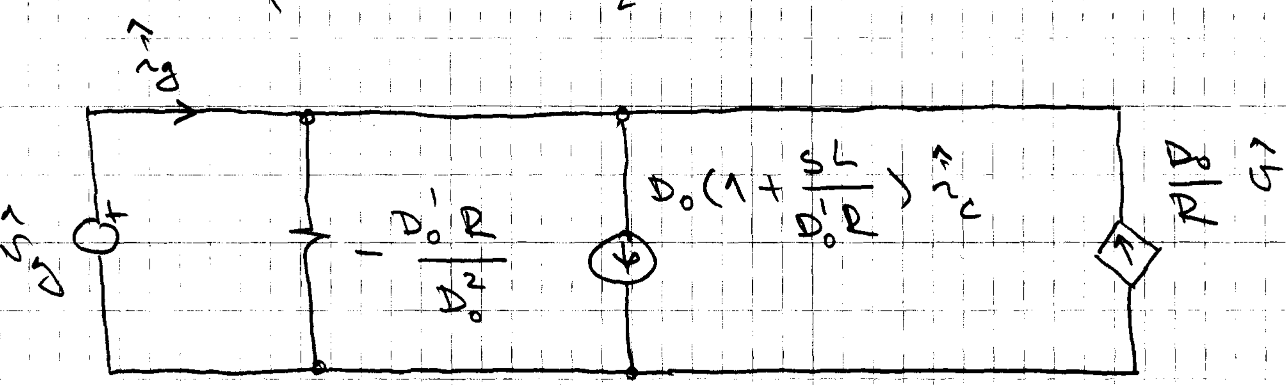
$$\hat{i}_g = \left(\frac{sLD_0}{RD_0'} + D_0\right)\hat{i}_c - \left(\frac{D_0}{R}\right)\hat{v} - \left(\frac{D_0^2}{D_0' R}\right)\hat{v}_g$$

← ово су основне једначине, следи елек. коло

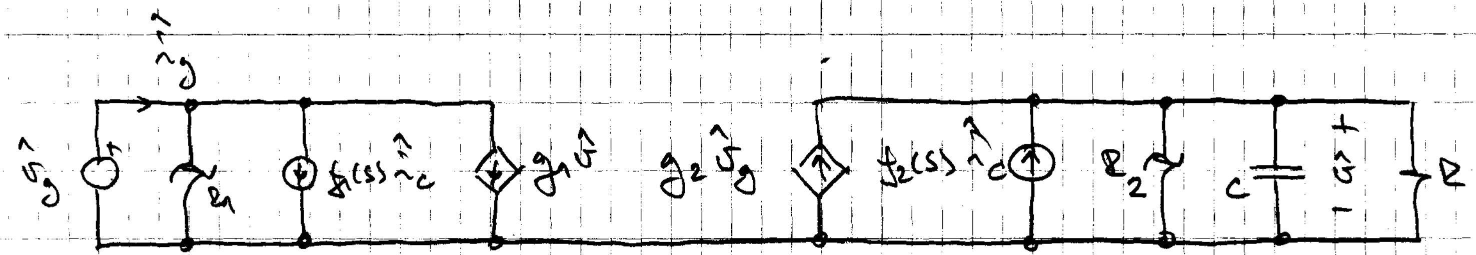
– једначина излазног кондензатора



– Line input current equation:



Спајањем:



$$R_1 = -\frac{D_0'}{D_0}R, \quad f_1(s) = D_0\left(1+s\frac{L}{D_0' R}\right), \quad g_1 = -\frac{D_0}{R}$$

$$R_2 = \frac{R}{D_0}, \quad f_2(s) = -D_0'\left(1-s\frac{D_0 L}{D_0'^2 R}\right), \quad g_2 = -\frac{D_0^2}{D_0' R}$$

Из овог кола се лако преносне функције, излазна импеданса, . . .

Summary: Control to output transfer function

$$\frac{\hat{v}}{\hat{i}_c} = j_2 \; R_2 \| R \| \frac{1}{sC} \qquad (\hat{v}_g = 0)$$

$$\boxed{\frac{\hat{v}}{\hat{i}_c} = -R \, \frac{1-D_0}{1+D_0} \, \frac{1 - s\dfrac{D_0 L}{D_0'^2 R}}{1 + s\dfrac{RC}{1+D_0}}}$$

line-to-output transfer function

$$\frac{\hat{v}}{\hat{v}_g} = g_2 \; R_2 \| R \| \frac{1}{sC} \qquad (\hat{i}_c = 0)$$

$$\boxed{\frac{\hat{v}}{\hat{v}_g} = -\frac{D_0^2}{1-D_0^2} \, \frac{1}{1 + s\dfrac{RC}{1+D_0}}}$$

output impedance

$$Z_{out} = R_2 \| R \| \frac{1}{sC} = \frac{R}{1+D_0} \, \frac{1}{1 + s\dfrac{RC}{1+D_0}}$$

$\hat{i}_c = 0, \quad \hat{v}_g = 0$

Пример 2: buck converter

$$sL\,\hat{i}(s) = \hat{d}\,V_g + D_0\,\hat{v}_g - \hat{v}$$

$$sC\,\hat{v}(s) = \hat{i} - \hat{v}/R$$

$$\hat{i}_g(s) = \hat{d}\,I_0 + D_0\,\hat{i}$$

С из state-space averaging-а

апроксимацията

$$\hat{i}(s) \cong \hat{i}_c(s)$$

$$sL\,\hat{i}_c(s) = \hat{d}\,V_g + D_0\,\hat{v}_g - \hat{v}$$

$$\hat{d}(s) \cong \frac{sL\hat{i}_c - D_0\hat{v}_g + \hat{v}}{V_g}$$

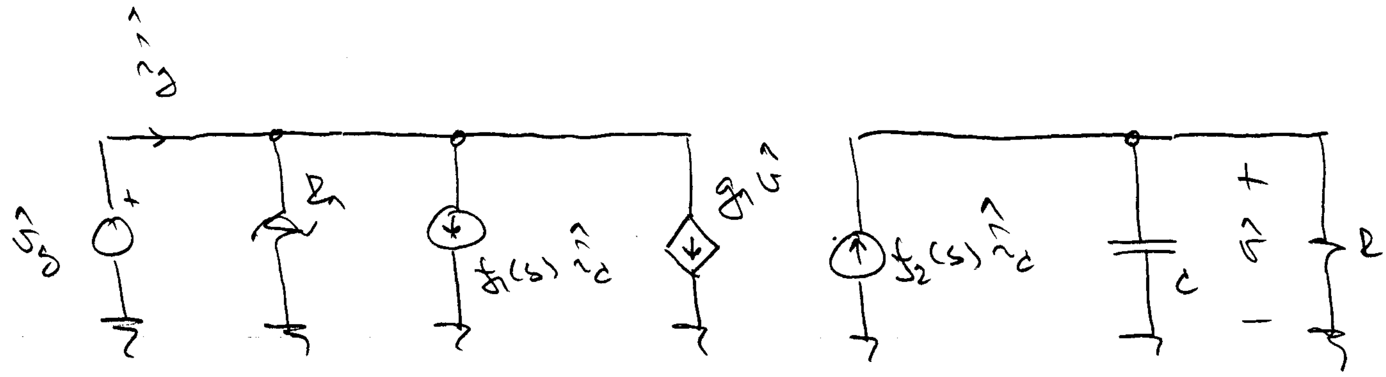
заменим $\hat{d}(s)$ и узем dc identity

$$I_0/V_g = D_0/R$$

$$sC\,\hat{v} = \hat{i}_c - \frac{\hat{v}}{R}$$

$$\hat{i}_g = \hat{i}_c D_0\left(1 + s\frac{L}{R}\right) - \frac{D_0^2}{R}\hat{v}_g + \frac{D_0}{R}\hat{v}$$

first-order small-signal equations



нема зависност од $\hat{v}_g$

$$R_1 = -\frac{R}{D_0^2}, \quad f_1(s) = D_0\left(1 + s\frac{L}{R}\right), \quad g_1 = \frac{D_0}{R},$$

$$f_2(s) = 1$$

control-to-output transfer function:

$$\frac{\hat{v}}{\hat{i}_c} = f_2(s)\, R \parallel \frac{1}{sC} = \frac{R}{1 + sRC}$$

line-to-output transfer function:

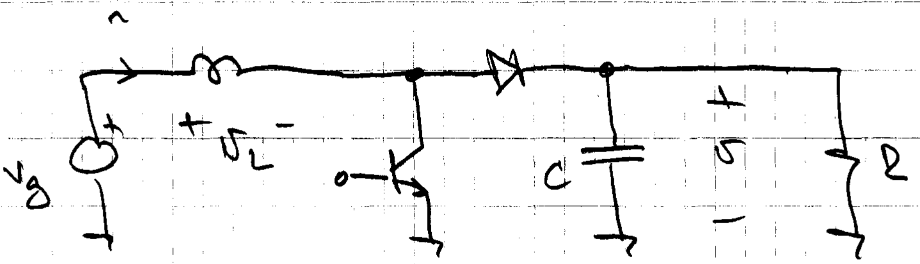
$$\frac{\hat{v}}{\hat{v}_g} = 0 \qquad \text{(good "line rejection")}$$

output impedance

$$Z_{out} = R \parallel \frac{1}{sC} = \frac{R}{1 + sRC}$$

(исто [illegible])

Вежба: CPM boost converter

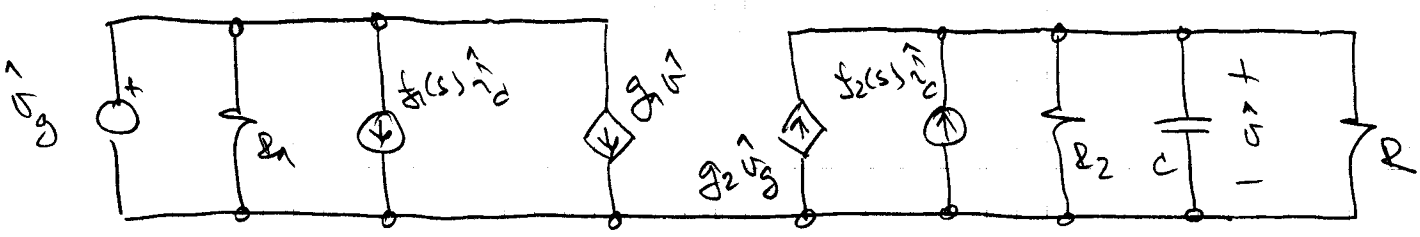


$$L \frac{d\hat{i}}{dt} = \hat{v}_g - D_0' \hat{v} + \hat{d} V_0$$

$$C \frac{d\hat{v}}{dt} = -\frac{\hat{v}}{R} + D_0' \hat{i} - \hat{d} I_0$$

даље сами . . .

A Canonical Model for the Current Programmed Mode



simple first-order model

converter	R_1	$f_1(s)$	g_1	g_2	$f_2(s)$	R_2
buck	$-\frac{R}{D_0^2}$	$D_0(1+s\frac{L}{R})$	$\frac{D_0}{R}$	0	1	∞
boost	∞	1	0	$\frac{1}{D_0' R}$	$D_0'(1-\frac{sL}{D_0'^2 R})$	R
buck-boost	$-\frac{D_0' R}{D_0^2}$	$D_0(1+s\frac{L}{D_0' R})$	$-\frac{D_0}{R}$	$-\frac{D_0^2}{D_0' R}$	$-D_0'(1-\frac{sD_0L}{D_0'^2 R})$	$\frac{R}{D_0}$