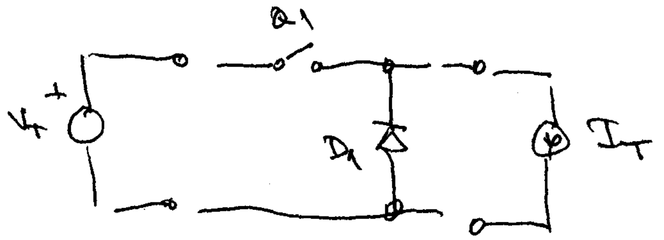
Квазирезонантни конвертори

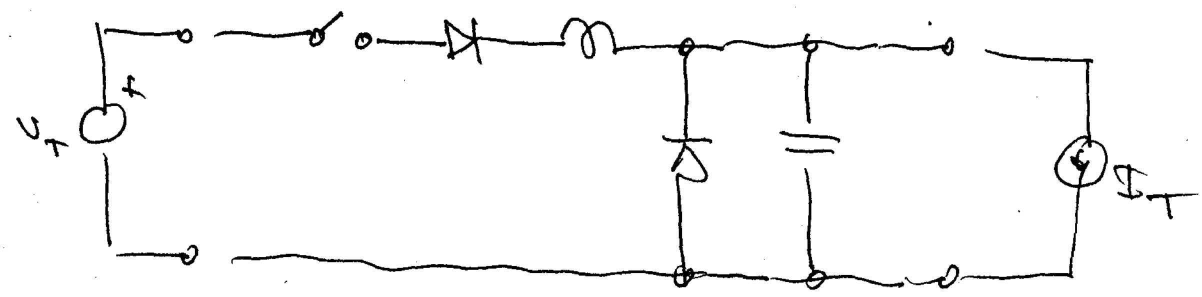
- модификација PWL конвертора са циљем да се смање switching loss.
- смањен (замена) switching, повећана conduction
  (1) мањи трансформатор и/или филтер са повећаним f_s
  (2) мањи sw loss од неидеалних компоненти L_s, C_{stray} капацитивности и сл., као и semiconductor device capacitances
- веома разнородно, може у масу апликација

Type a zero Current switch

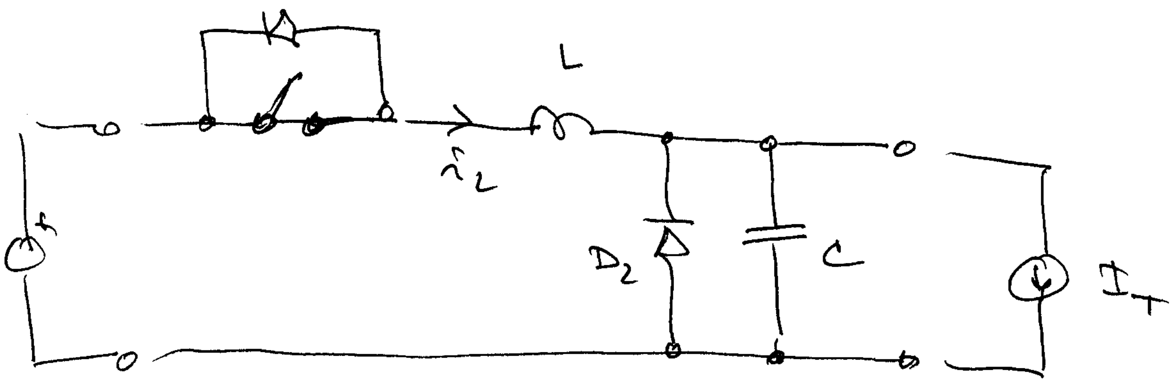
Standard PWM



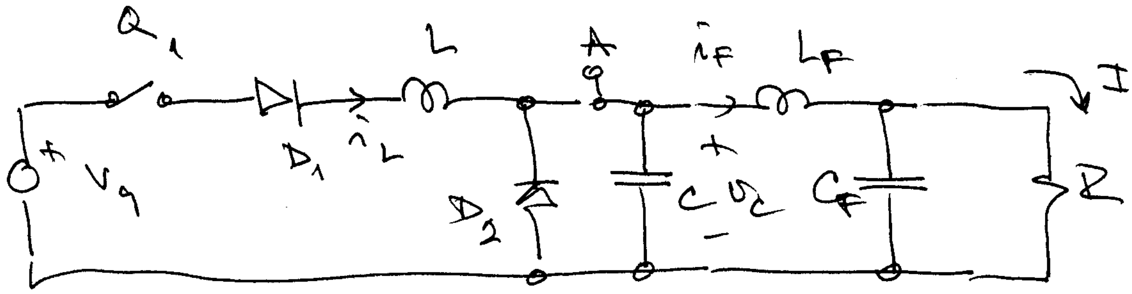
Half-wave ZCC



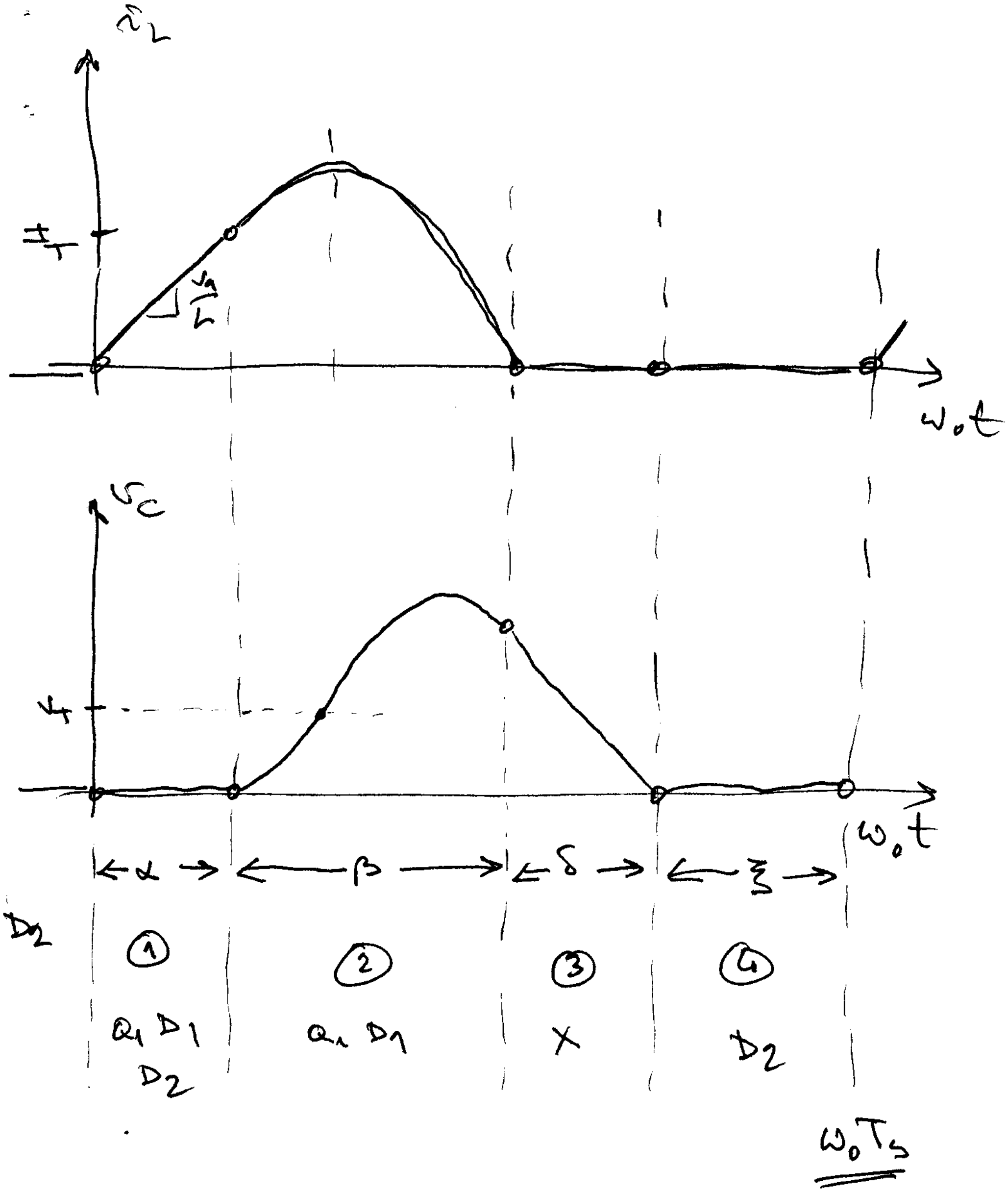
Full wave ZCS



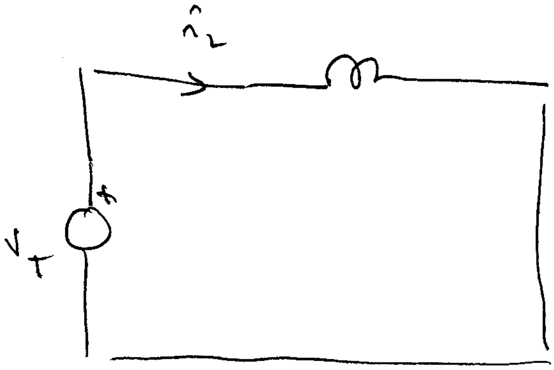
Buck converter Example



$i_F = I$



1

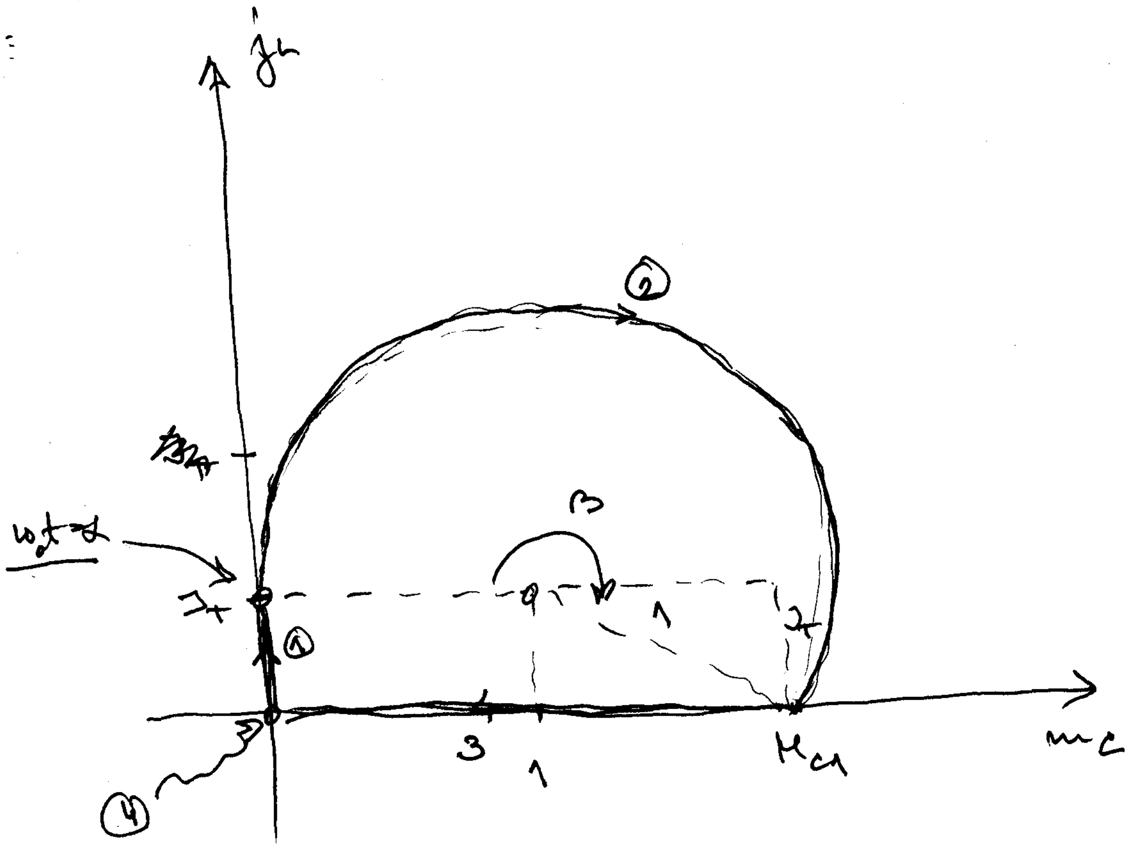


$$V_{base} = V_T$$

$$R_{base} = R_0 = \sqrt{\frac{L}{C}}$$

$$I_{base} = V_T / R_0$$

$$f_{base} = f_0 = \frac{1}{2\pi\sqrt{LC}}$$



$$\frac{1}{\omega_0}\frac{dj_L}{dt} = 1 \qquad j_L(0) = 0$$

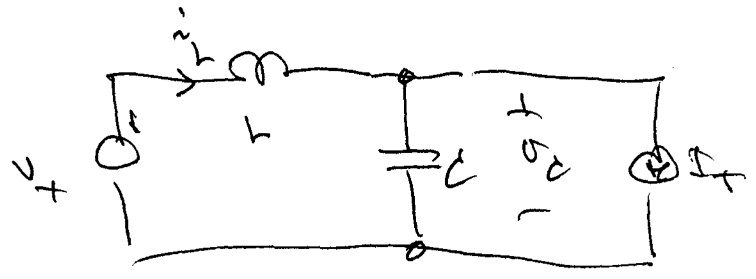
$$\Rightarrow \; j_L(\omega_0 t) = \omega_0 t \qquad m_C(\omega_0 t) = 0 \quad \text{II ј-на}$$

D_2 се гаси кад i_L достигне I_T

$i_L = I_T \quad \omega_0 t = \alpha$ — interval ends

$$\boxed{j_L(\alpha) = J_T = \alpha} \qquad \text{(solution for } \alpha\text{)}$$

Interval 2



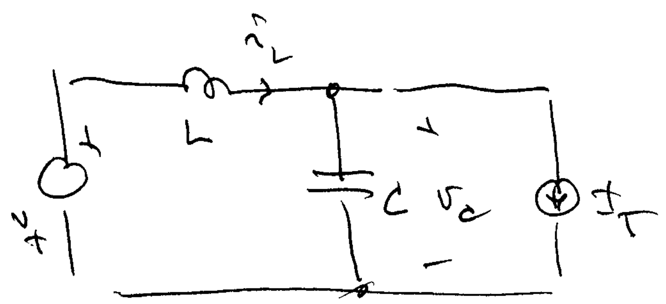
$$L\frac{di_L}{dt} = V_T - v_C \qquad \frac{1}{\omega_0}\frac{dj_L}{dt} = 1 - m_C$$

$$C\frac{dv_C}{dt} = i_L - I_T \qquad \frac{1}{\omega_0}\frac{dm_C}{dt} = j_L - J_T$$

Трајекторија је кружни лук са центром на

$(m_C, j_L) = (1, J_T)$

$$q_2 = \int_{\frac{\alpha}{\omega_0}}^{\frac{\alpha+\beta}{\omega_0}} i_L \, dt$$



$$q_2 = \underbrace{\int_{\frac{\alpha}{\omega_0}}^{\frac{\alpha+\beta}{\omega_0}} i_C \, dt}_{\begin{array}{l} = q_C = C \Delta v_C \\ = C(V_{ca} - 0) = \\ = C V_{ca} \end{array}} + \underbrace{\int_{\frac{\alpha}{\omega_0}}^{\frac{\alpha+\beta}{\omega_0}} I_T \, dt}_{= I_T \frac{\beta}{\omega_0}} = C V_{ca} + I_T \frac{\beta}{\omega_0}$$

$$\overline{i_L} = \frac{1}{T_s} \left(\frac{1}{2} \frac{\alpha}{\omega_0} I_T + C V_{ca} + I_T \frac{\beta}{\omega_0} \right) =$$

$$= \frac{1}{\omega_0 T_s} \left(\frac{1}{2} \alpha I_T + \omega_0 C V_{ca} + \beta I_T \right)$$

$$\overline{j_L} = \frac{F}{2\pi} J_T \left(\frac{1}{2} \alpha + \beta + \frac{M_{ca}}{J_T} \right)$$

$$\overline{j_L} = J_T F \frac{1}{2\pi} \left(\frac{1}{2} J_T + \pi + \arcsin J_T + \frac{1}{J_T} \left(1 + \sqrt{1 - J_T^2} \right) \right)$$

$$\boxed{j_{L\,peak} = 1 + J_T}$$

$$\boxed{m_{c\,peak} = 2}$$

$$\boxed{\beta = \pi + \sin^{-1} J_T}$$

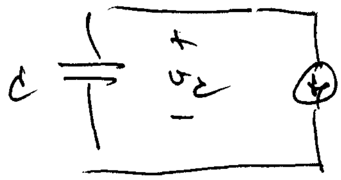
$j_L(\alpha+\beta) = 0$ – гаси се Q_1 D_1

$m_c(\alpha+\beta) = M_{c1} = 1 + \sqrt{1 - J_T^2}$

$$\boxed{J_T \leq 1}$$

Interval ③

$$C\frac{dv_c}{dt} = -I_T, \quad v_c(\alpha+\beta) = V_{c1}$$



$$\frac{1}{\omega_0}\frac{dm_c}{dt} = -J_T, \quad m_c(\alpha+\beta) = M_{c1}$$

$$m_c(\omega_0 t) = M_{c1} - J_T(\omega_0 t - \alpha - \beta)$$

завршава се када $v_c = 0$, D_2 почне да проводи

$$m_c(\alpha+\beta+\delta) = 0 = M_{c1} - J_T\delta$$

$$\delta = \frac{M_{c1}}{J_T} = \frac{1}{J_T}\left(1 + \sqrt{1 - J_T^2}\right)$$

Interval 4

исто као $D'T_s$ интервал код PWL

$\hat{i}_L = 0$ $\quad\quad$ $\hat{j}_L = 0$

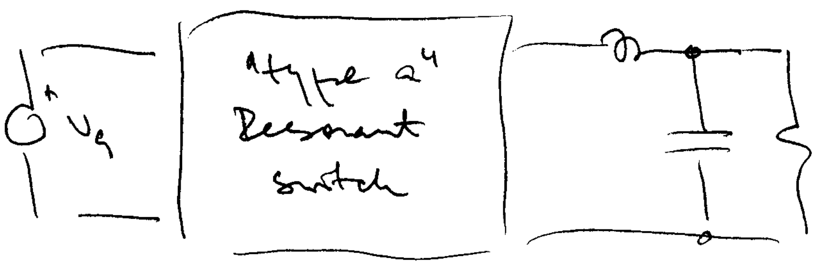
$\hat{v}_c = 0$ $\quad\quad$ $m_c = 0$

$$\omega_0 T_s = \alpha + \beta + \delta + \xi$$

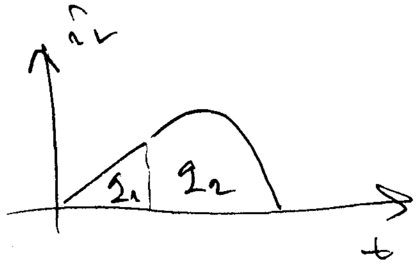
minimum switching interval

$$\underline{\omega_0 T_s \geq \alpha + \beta + \delta} \qquad (\underline{\xi > 0})$$

усредњавање



$$\bar{\hat{i}}_L = \frac{1}{T_s}\int_0^{T_s} \hat{i}_L \, dt = \frac{q_1 + q_2}{T_s}$$



$$q_1 = \int_0^{\alpha/\omega_0} \hat{i}_L \, dt = \frac{1}{2}\left(\frac{\alpha}{\omega_0}\right) I_T$$

$P_{out} = P_{in}$

$\overline{I_T} \langle v_c \rangle = \overline{V_T} \langle \hat{i}_L \rangle$

$J_T \, \overline{m_c} = 1 \cdot \overline{\hat{j}_L}$

$\Leftarrow \quad \overline{m_c} = \frac{1}{J_T} \overline{\hat{j}_L}$

$$\overline{m_c} = F \underbrace{\frac{1}{2\pi} \left(\frac{1}{2} J_T + \pi + \sin^{-1} J_T + \frac{1}{J_T} \left(1 + \sqrt{1 - J_T^2}\right)\right)}_{P(J_T)}$$

$$\boxed{\overline{m_c} = F \, P(J_T)}$$

Switch conversion ratio

$$\mu = \frac{\langle v_c \rangle}{V_T} = \frac{\langle \hat{j}_L \rangle}{J_T} = F P(J_T) \qquad \cancel{F = \frac{f_s}{f_0}}$$

controlable by $F = \frac{f_s}{f_0}$

depends on $J_T = \frac{I_T R_0}{V_T}$

Output Plane

Mode Boundaries:

1. $J_T \leq 1$ - otherwise no zero current switching

2. $\xi \geq 0 \Rightarrow \frac{2\pi}{F} \geq \alpha + \beta + \delta$

$$\frac{2\pi}{F} \geq J_T + \pi + \sin^{-1} J_T + \frac{1}{J_T}\left(1 + \sqrt{1 - J_T^2}\right)$$

$$\frac{2\pi}{F} \geq \frac{2\pi}{F}\langle m_c \rangle + \frac{1}{2} J_T$$

$$\langle M_c \rangle \leq 1 - \frac{J_T F}{4\pi} < 1$$

$$0 \leq \langle m_c \rangle \leq 1 - \frac{J_T F}{4\pi}$$

$$0 \leq J_T \leq 1$$

3a buck

$$M = \frac{V}{V_g} = \langle m_c \rangle$$

$$J = \frac{I R_o}{V_g} = J_T$$

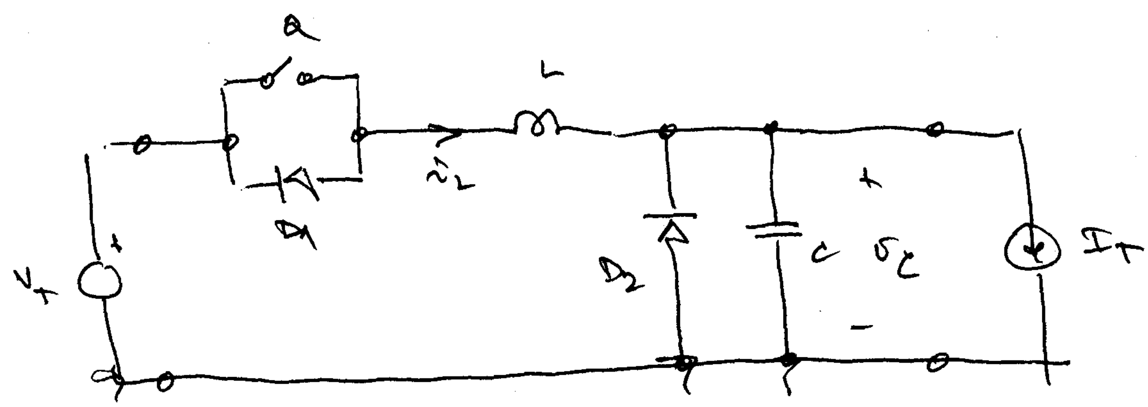
- Control Plane Characteristics – учење од рачунка.

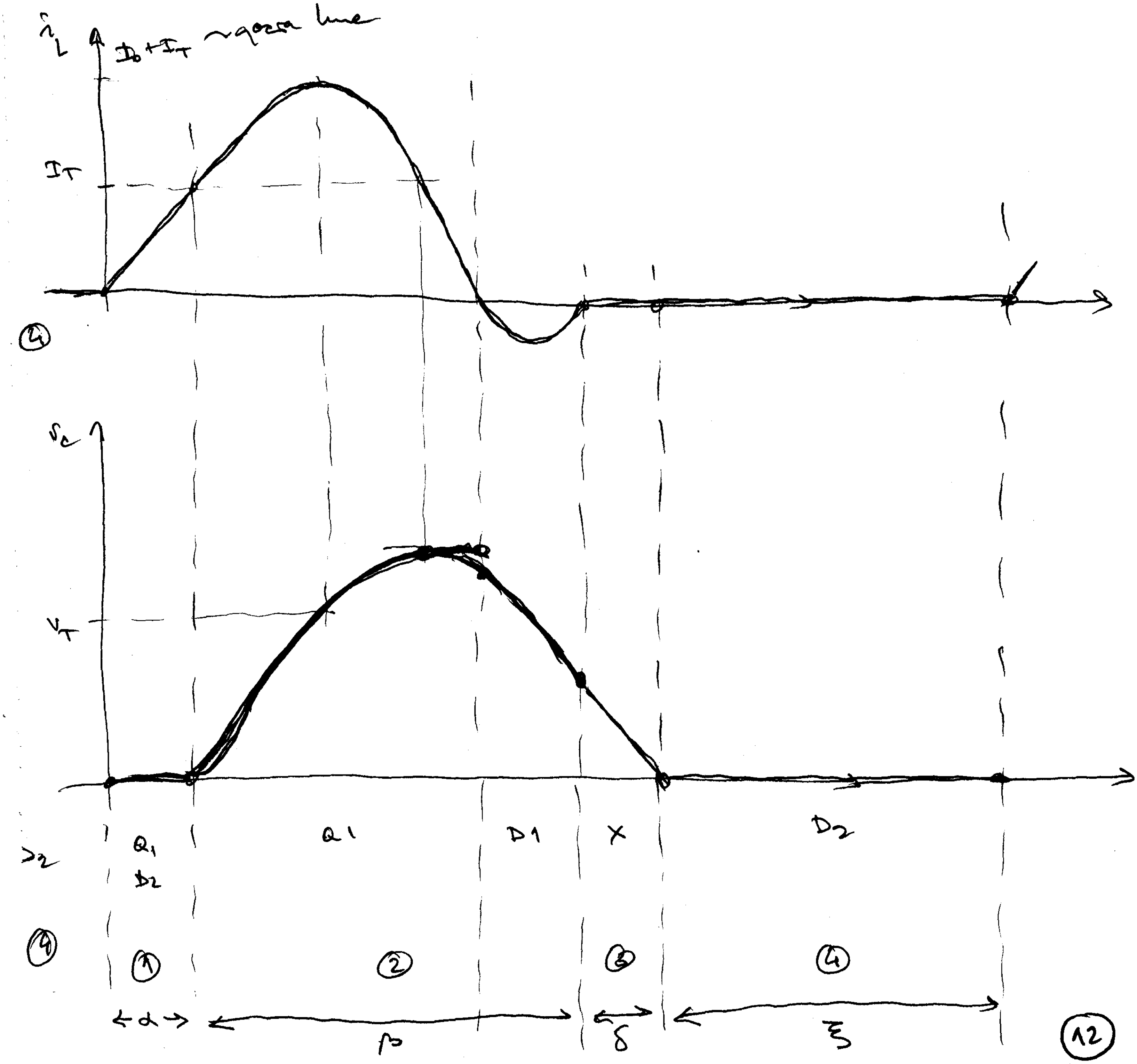
$M = JQ$ $\qquad$ Q – сопствено R ...

$M = FP\left(\frac{M}{Q}\right)$ – мора нумеричка

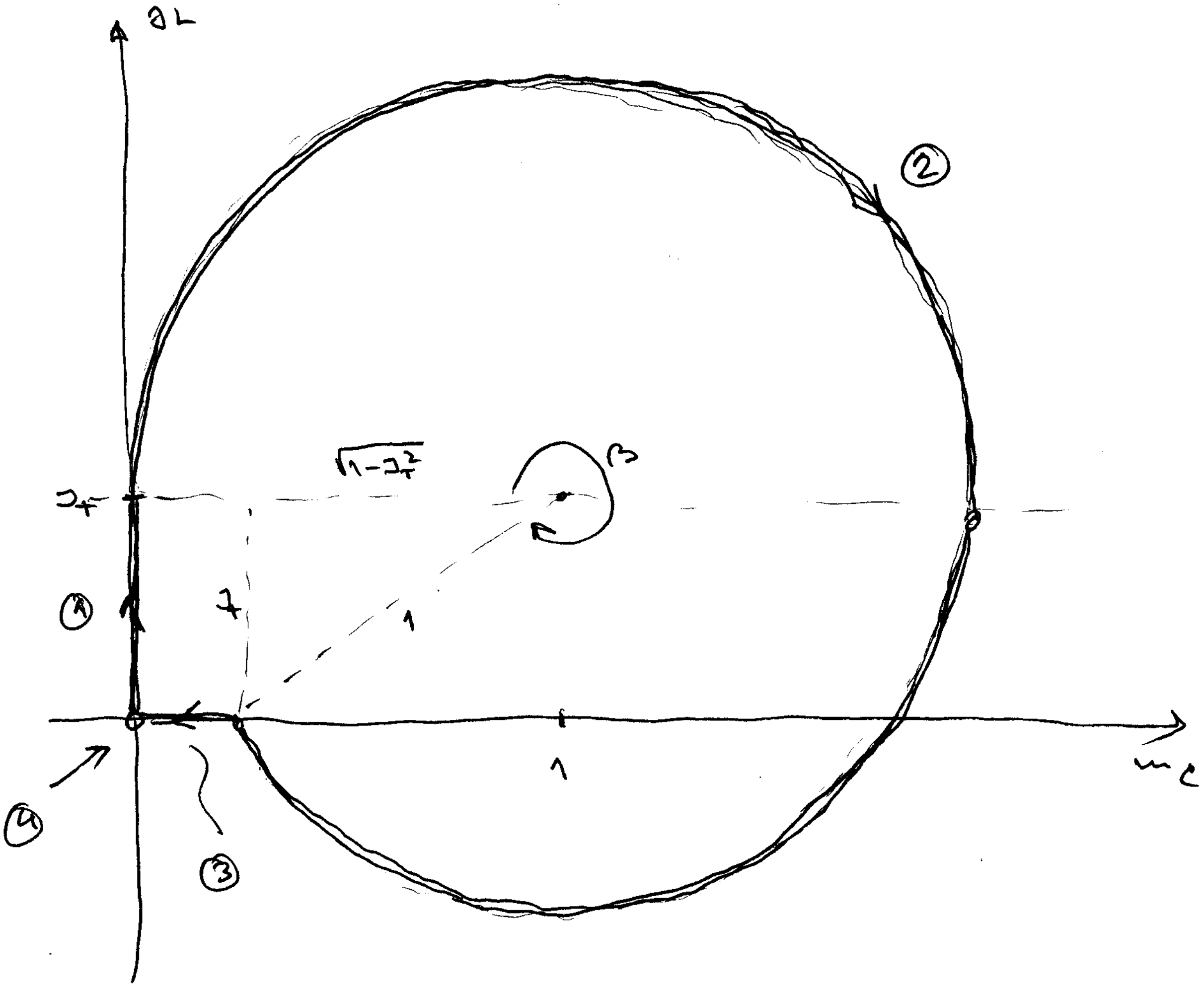
јако нелинеарно

Full Wave : "type a" zero current switch





Normalized State Plane



Анализа је иста као и за half-wave case, осим за интеграл ②

$$\beta = \begin{cases} \pi + \arcsin J_T & \text{— half wave} \\ 2\pi - \arcsin J_T & \text{— full wave} \end{cases}$$

$$M_{cn} = \begin{cases} 1 + \sqrt{1 - J_T^2} & \text{— half wave} \\ 1 - \sqrt{1 - J_T^2} & \text{— full wave} \end{cases}$$

У оба случаја

$$\langle m_c \rangle = F \frac{1}{2\pi} \left(\frac{1}{2} \alpha + \beta + \frac{M_{cn}}{J_T} \right)$$

замена

$$\bar{m}_c = F \frac{1}{2\pi} \left(\frac{1}{2} J_T + 2\pi - \arcsin J_T + \frac{1}{J_T} \left(1 - \sqrt{1 - J_T^2}\right) \right)$$

In general, switch conversion ratio can be written as

$P(J_T) \cong 1$ (унутар 4%)

$$\mu = \frac{\bar{v}_c}{V_T} = \bar{m}_c = F\,P(J_T) \cong F \text{ (within 4\%)}$$

$P(J_T)$ се мења у ~~зависности~~ зависности од случаја (half / full wave).

Решење:

$$\mu = \frac{\hat{v}_c}{V_T} = \bar{m}_c = F\,P(J_T)$$

half-wave: $P(J_T) = k_{1/2}(J_T) \triangleq \frac{1}{2\pi}\left(\frac{J_T}{2} + \pi + \arcsin J_T + \frac{1}{J_T}\left(1+\sqrt{1-J_T^2}\right)\right)$

full-wave: $P(J_T) = k_{1}(J_T) \triangleq \frac{1}{2\pi}\left(\frac{J_T}{2} + 2\pi - \arcsin J_T + \frac{1}{J_T}\left(1-\sqrt{1-J_T^2}\right)\right)$

за full-wave case:

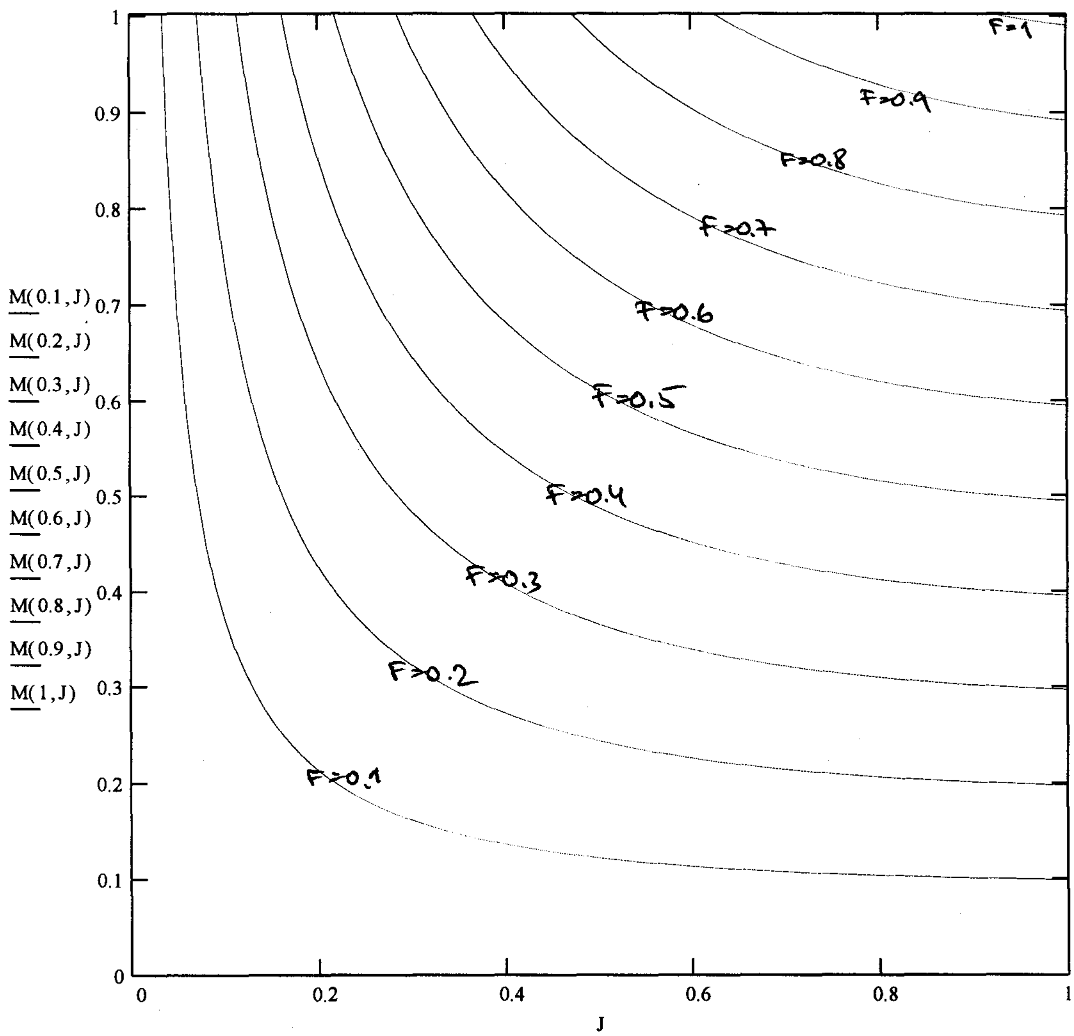
$\mu \cong F = \frac{f_s}{f_0}$ voltage source, controllable by F, исто као PWM са $D \to F$

за switching regulator, full-wave варијанта мора имати шири frequency range него half-wave да би се регулисао излаз

$$P(J) := \frac{1}{2\cdot\pi}\cdot\left[\frac{1}{2}\cdot J + \pi + \operatorname{asin}(J) + \frac{1}{J}\cdot\left(1+\sqrt{1-J^2}\right)\right]$$

$$M(F,J) := F\cdot P(J)$$

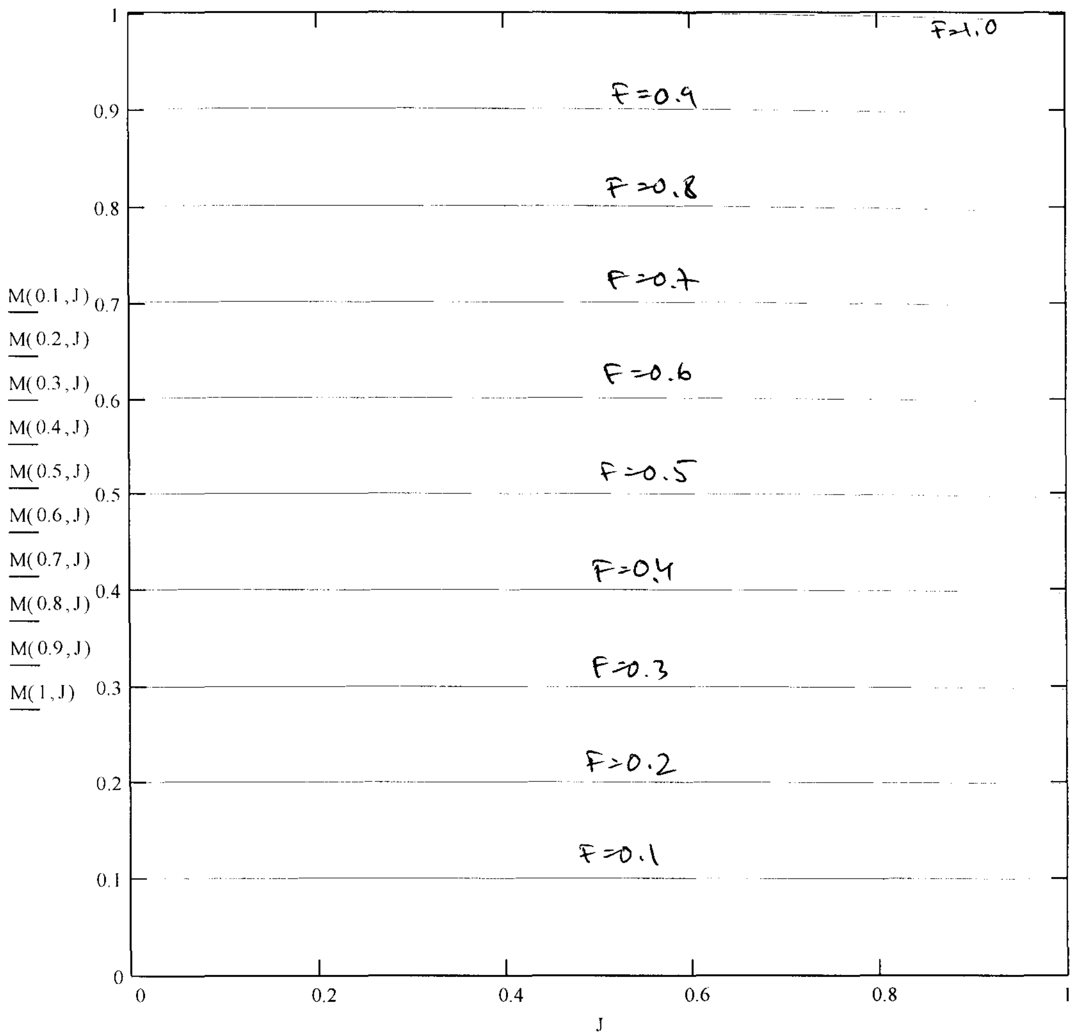
$$J := 0.01, 0.02 .. 1$$



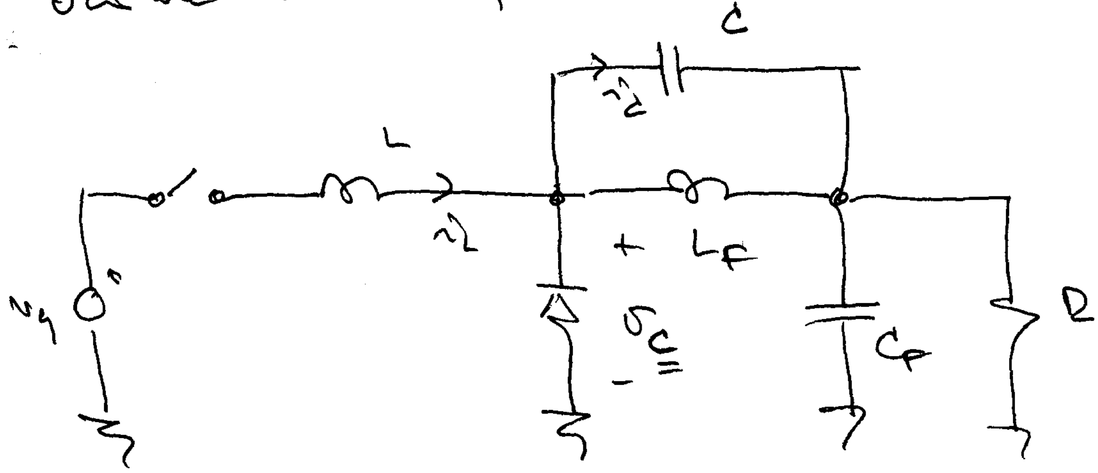
$$P(J) := \frac{1}{2\cdot\pi}\cdot\left[\frac{1}{2}\cdot J + 2\cdot\pi - \mathrm{asin}(J) + \frac{1}{J}\cdot\left(1 - \sqrt{1 - J^2}\right)\right]$$

$$M(F,J) := F\cdot P(J)$$

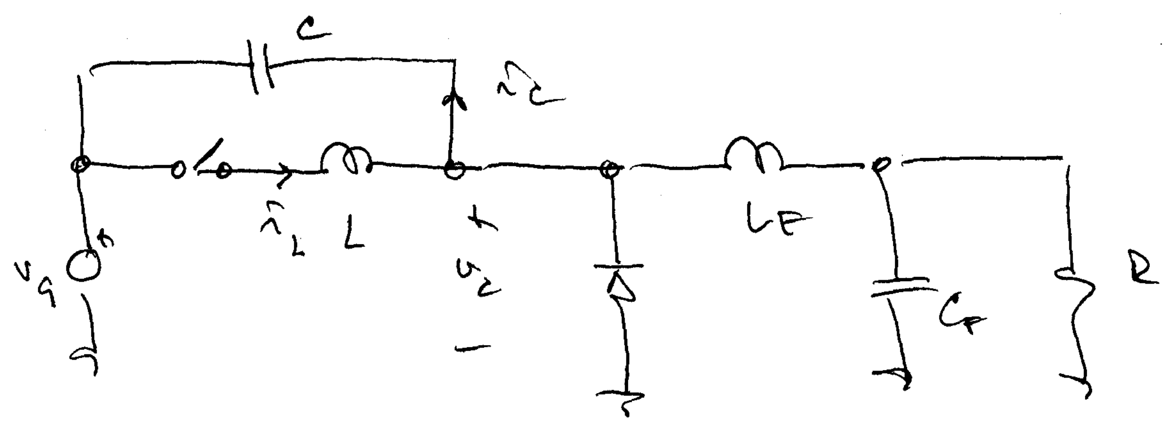
$$J := 0.01, 0.02 .. 1$$



Остале топологије



исти [illegible] ZCS и ZVS

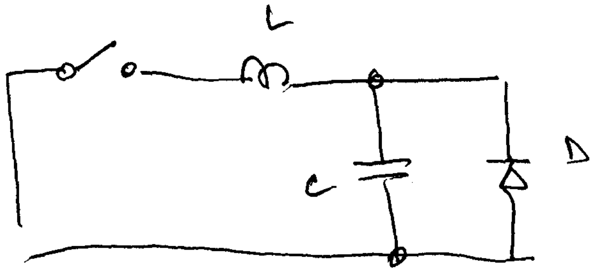


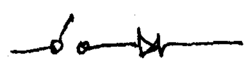
исто ZCS и ZVS, type a resonant switch

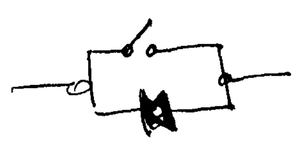
<u>Тест за тип резонантног прекидача</u>

V, C_R → [illegible]
I, L_F → [illegible]

type "a" се [illegible] [illegible] [illegible]

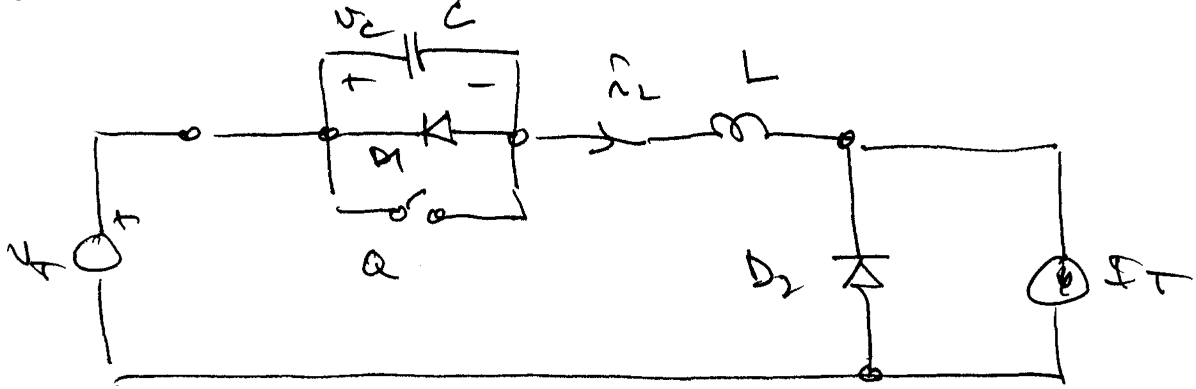


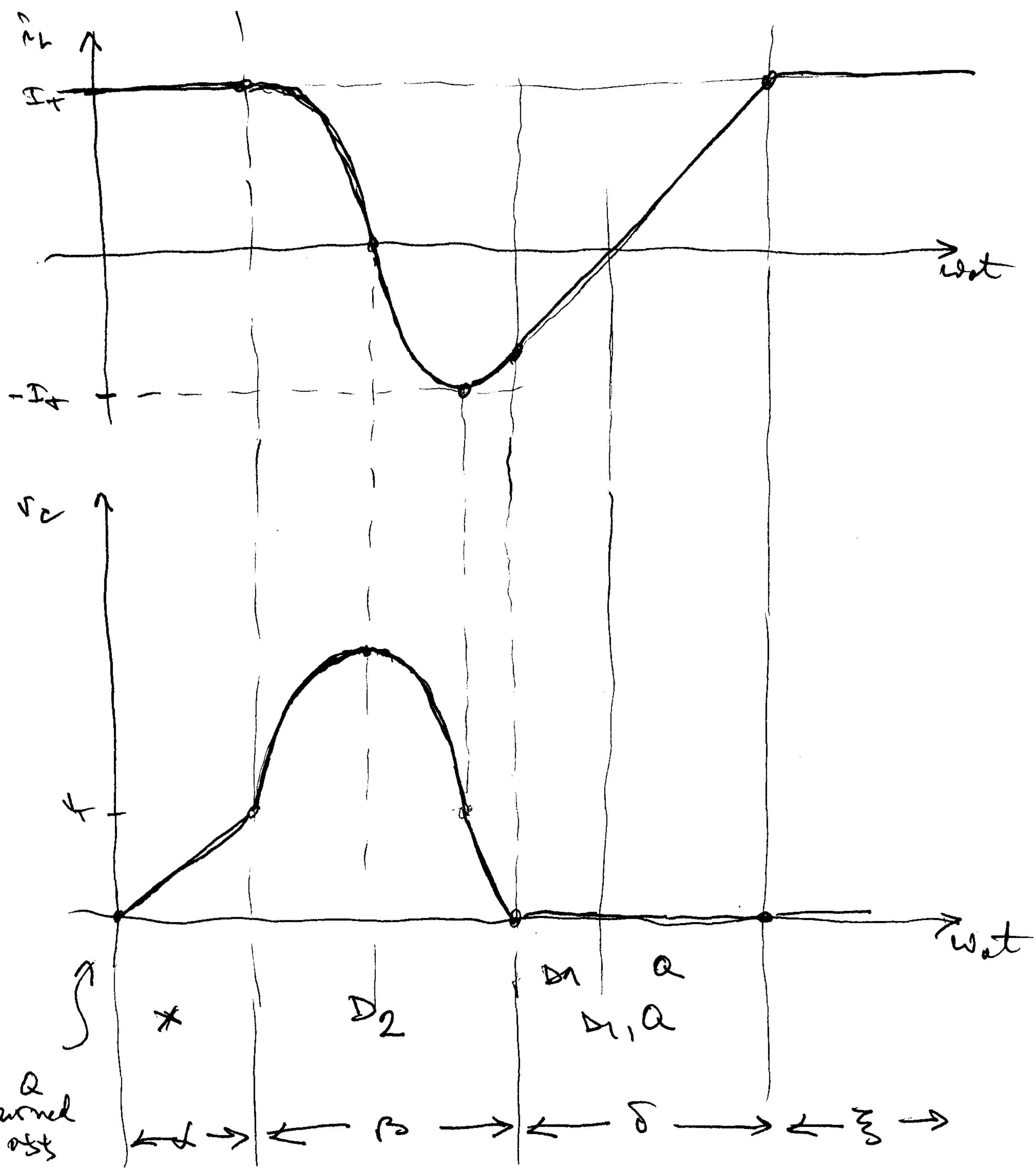

– half wave

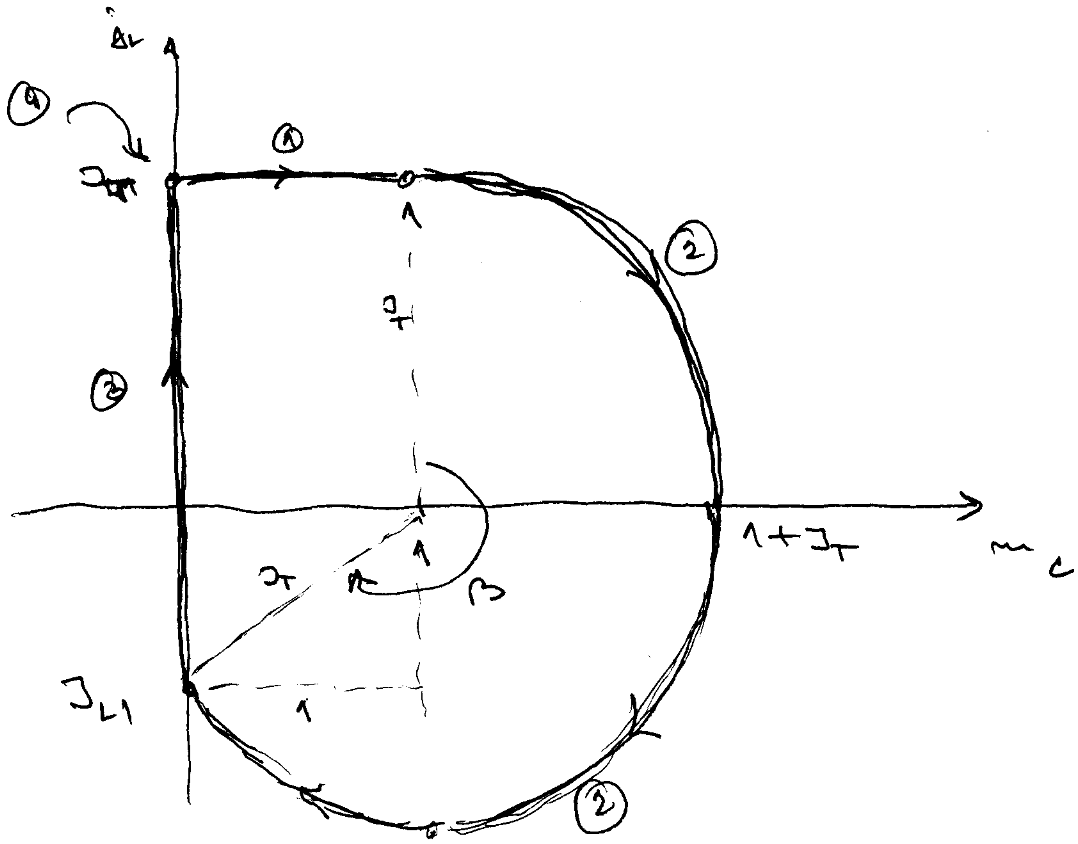

– full wave

The Zero-Voltage resonant switch
"type 6" ZVS

Basic Network



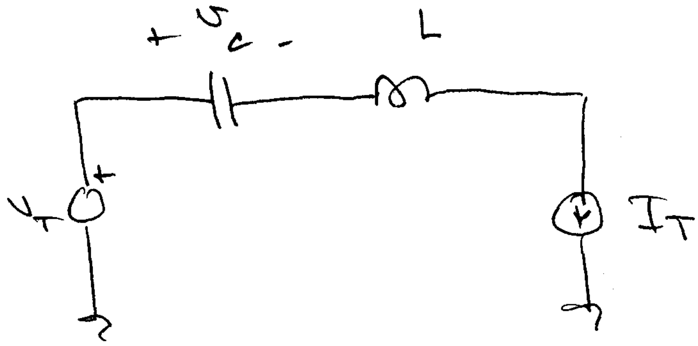




$$J_{L1} = \sqrt{J_T^2 - 1}$$

(a) – исто када се Q искључи.

– у почетку је искључено



коло денормализујемо

$$v_c = 0 + \frac{I_T}{C} \cdot t = \frac{I_T}{C} \cdot t$$

$$\frac{1}{\omega_0} \dot{m}_c = I_T \qquad m_c(0) = 0$$

$$m_c = I_T \omega_0 t$$

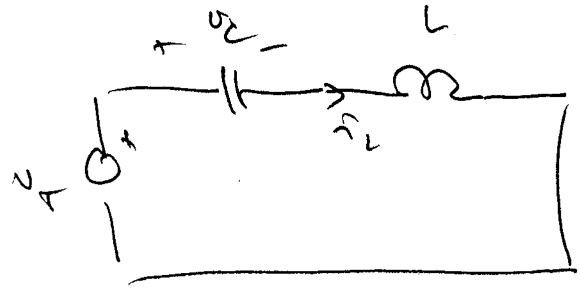
одакле се лако одреди α

$$m_c(\alpha) = 1$$

$$1 = I_T \alpha$$

$$\boxed{\alpha = \frac{1}{I_T}}$$

② води D_2



улазак у $(u_C, j_L) = (1, 0)$

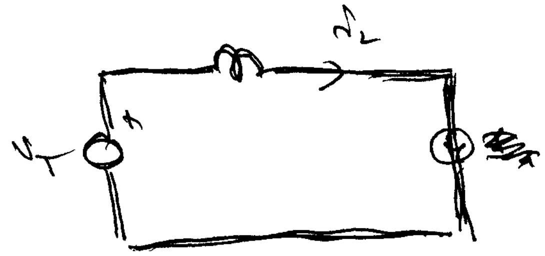
иде док не укључи диоду D_1 $(u_C > 0)$

$$\beta = \pi + \arcsin \frac{1}{J_T}$$

$$J_{L1} = \sqrt{J_T^2 - 1}$$

$\underline{J_T \geq 1}$ – <u>заглави се</u>

③ Угашена D_1 (касније и Q_1), води D_2



$$\frac{1}{\omega_0} \frac{dj_L}{dt} = 1 \qquad j_L(\alpha + \beta) = -J_{L1}$$

$$j_L(\omega_0 t) = -J_{L1} + \omega_0 t - (\alpha + \beta)$$

заглавиће се кад

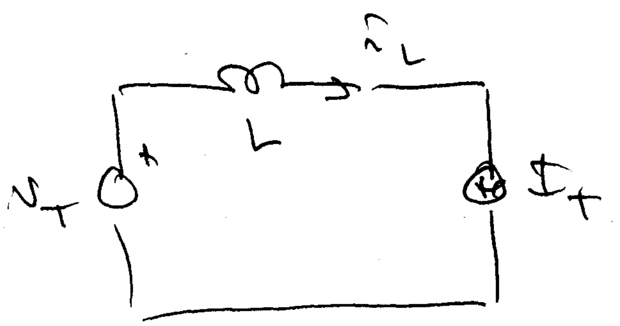
$$j_L(\alpha + \beta + \delta) = J_T$$

$$J_T = -J_{L1} + \delta$$

$$\boxed{\delta = J_T + J_{L1} - J_T + \sqrt{J_T^2 - 1}}$$

Interval 4 $\quad Q_x$ vodi

$$\alpha + \beta + \delta \le \omega_0 t \le \alpha + \beta + \delta + \zeta\,)$$

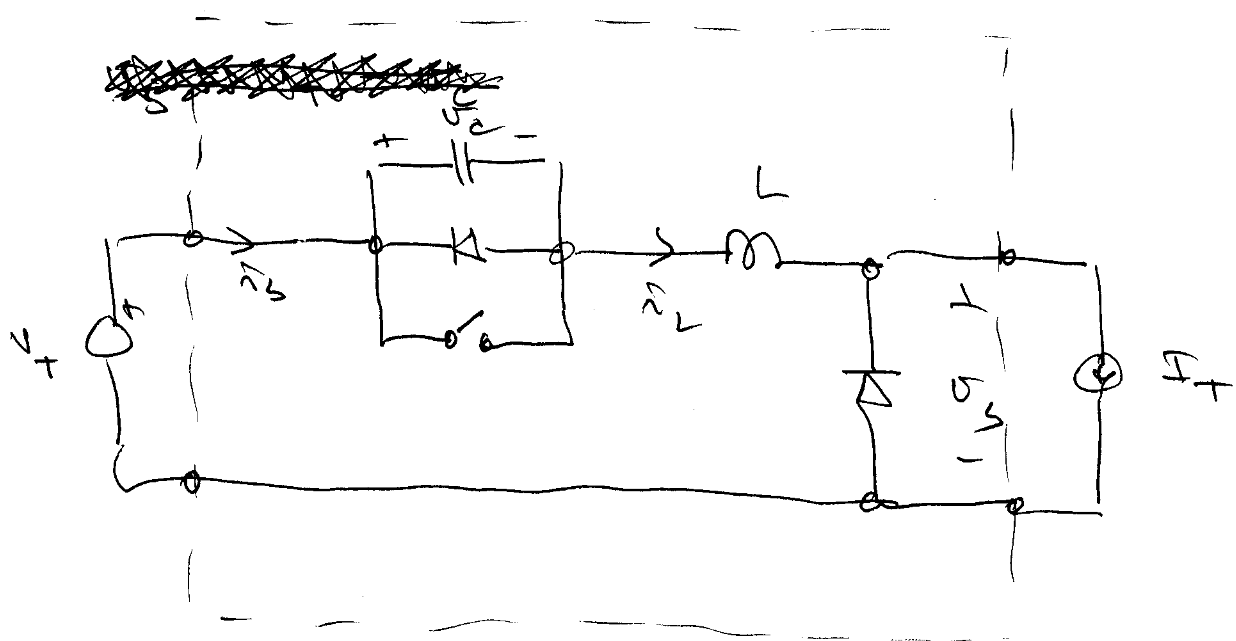


$$i_L = I_T$$

$$v_C = 0$$

a vodi, druge neprovodno

Усредњавање



$$v_S = V_T - v_C - v_L$$

$$\overline{v_S} = \cancelto{V_T}{\overline{V_T}} - \overline{v_C} - \cancelto{0}{\overline{v_L}}$$

$$\overline{v_S} = V_T - \overline{v_C}$$

Нормализација:

$$\langle m_S \rangle = 1 - \langle m_C \rangle$$

циљ: рачун $\overline{m_C}$

$$\bar{v}_c = \frac{1}{T_s}\int_0^{T_s} v_c(t)\,dt = \frac{\lambda_1+\lambda_2}{T_s}$$

$$\lambda_1 = \frac{1}{2}\left(\frac{\alpha}{\omega_0}\right)(V_T)$$

λ_2 - flux-linkage arguments

интервал 2

$$v_c = V_T - v_L$$

$$\lambda_2 = \int_{\frac{\alpha}{\omega_0}}^{\frac{\alpha+\beta}{\omega_0}} v_c\,dt = \int_{\frac{\alpha}{\omega_0}}^{\frac{\alpha+\beta}{\omega_0}} V_T\,dt + \int_{\frac{\alpha}{\omega_0}}^{\frac{\alpha+\beta}{\omega_0}} v_L\,dt = \lambda_T + \lambda_L$$

$$\boxed{\lambda_T = V_T\frac{\beta}{\omega_0}}$$

$\lambda_L = L\Delta i_L$ - KE у интегралној форми

$$\boxed{\lambda_L = L\left(i_L\left(\frac{\alpha+\beta}{\omega_0}\right) - i_L\left(\frac{\alpha}{\omega_0}\right)\right) = L(-I_{L1}-I_T)}$$

$$\lambda_2 = V_T\frac{\beta}{\omega_0} - L(-I_{L1}-I_T)$$

$$\bar{\sigma}_2 = \frac{\lambda_1 + \lambda_2}{T_s} =$$

$$= \frac{1}{\omega_0 T_s} \left(\frac{1}{2} \alpha V_T + \beta V_T + \omega_0 L (I_{L1} + I_T) \right)$$

нормализирано:

$$\bar{m}_c = \frac{F}{2\pi} \left(\frac{1}{2} \alpha + \beta + J_{L1} + J_T \right)$$

замена за α, β и J_{L1}

$$\bar{m}_c = \frac{F}{2\pi} \left(\frac{1}{2} \frac{1}{J_T} + \pi + \arcsin\left(\frac{1}{J_T}\right) + \right.$$

$$\left. + J_T + \sqrt{J_T^2 - 1} \right)$$

$$= F\, P(J_T)$$

исто како и за half-wave zero current (type a) switch, само што на место J_T иде $\frac{1}{J_T}$

Средња вредност излазног напона

$$\overline{m_s} = 1 - \overline{m_c}$$

$$\overline{v_s} = \mu V_T \qquad \mu = 1 - FP(J_T)$$

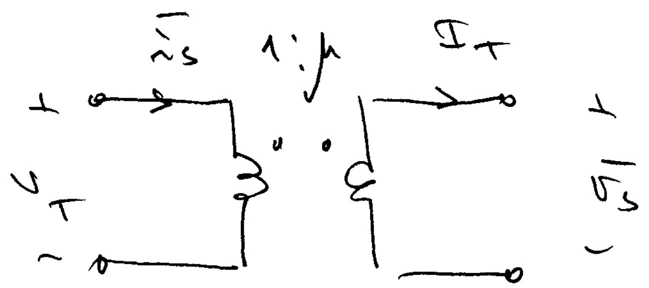
$$P = \frac{1}{2\pi}\left(\frac{1}{2}\,\frac{1}{J_T} + \pi + \arcsin\frac{1}{J_T} + J_T + \sqrt{J_T^2 - 1}\right)$$

средња вредност улазне струје, ЗОЕ

$$V_T \langle i_s \rangle = \langle v_s \rangle I_T$$

$$\overline{v_s} = \mu V_T$$

$$\overline{i_s} = \mu I_T$$



Current формуле за full-wave case

$P \cong 1 \qquad \mu \cong 1 - F$

Решење формулама за type a и type b

Switch	μ	$P(J_T)$	load range
PWM	D	—	∞
type a $\frac{1}{2}$ wave	$F\,P(J_T)$	$k_{1/2}(J_T)$	$0 \le J_T \le 1$
type a 1 wave	$F\,P(J_T) \cong F$	$k_1(J_T) \cong 1$	$0 \le J_T \le 1$
type b $\frac{1}{2}$ wave	$1 - F\,P(J_T)$	$k_{1/2}\left(\frac{1}{J_T}\right)$	$1 \le J_T \le \infty$
type b 1 wave	$1 - F\,P(J_T) \cong 1 - F$	$k_1\left(\frac{1}{J_T}\right) \cong 1$	$1 \le J_T \le \infty$

за све је $0 \le \mu \le 1$

$$k_{1/2}(x) = \frac{1}{2\pi}\left(\frac{1}{2}x + \pi + \arcsin x + \frac{1}{x}\left(1 + \sqrt{1 - x^2}\right)\right)$$

$$k_1(x) = \frac{1}{2\pi}\left(\frac{1}{2}x + 2\pi - \arcsin x + \frac{1}{x}\left(1 - \sqrt{1 - x^2}\right)\right)$$

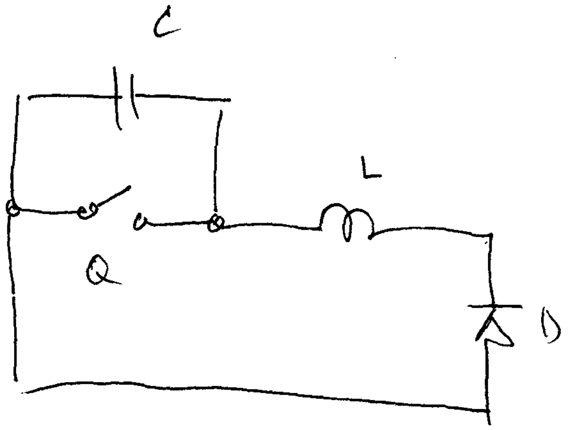
карактеристике овог типа ~~типа~~ "type a" резонантног прекидача

1) zero-current switching
2) peak switch currents знатно веће од I_F
3) peak switch voltages — V_q, исто као у PWM

Остале топологије:

Type b resonant switch

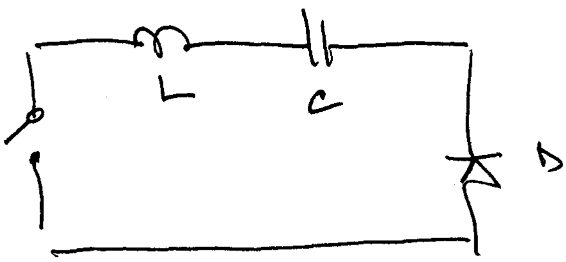
1 zero voltage switching
2 максималне струје прекидача исте као код PWM
3 повећани напон на прекидачу
4 дуални тип type-a прекидачу
- своди се на



Type C Resonant Switch

1. zero current switching
2. [illegible] [illegible] [illegible] ca PWM
3. [illegible] blocking voltage

- diagram ca 4a



Type d resonant switch

- zero voltage switching
- максимални напон као код конвенционалног PWM
- максималне струје прекидача повећане
- дуално to type c switch

- добија се на