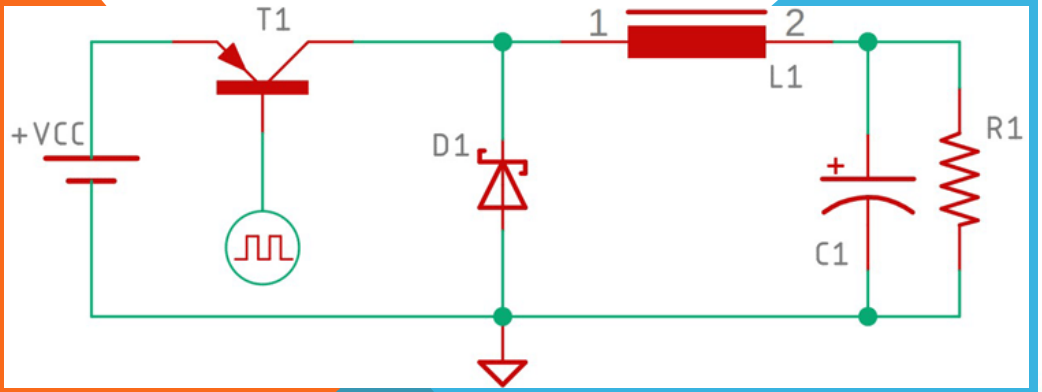
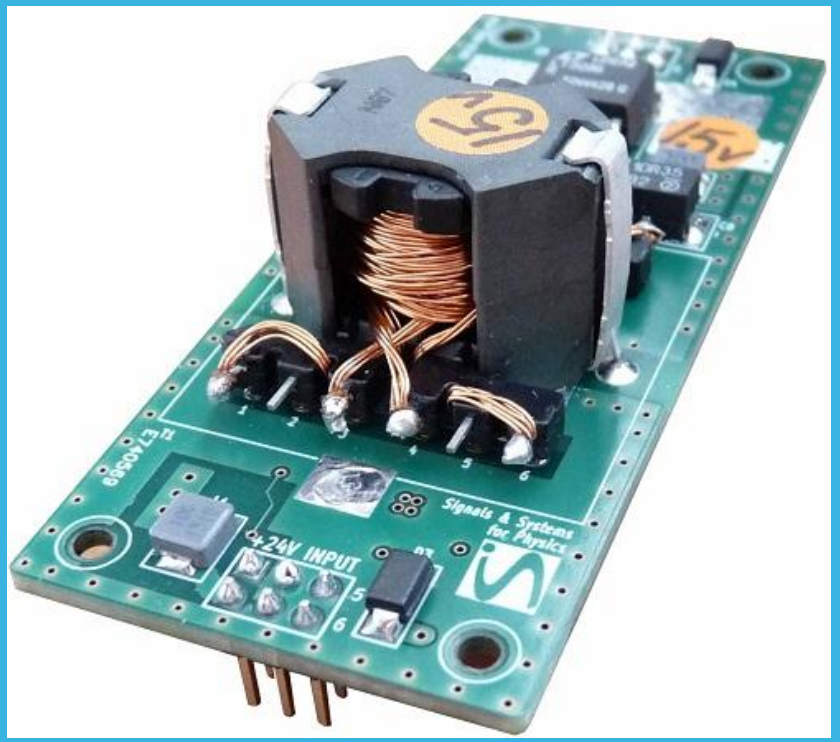
VISOKA ŠKOLA ELEKTROTEHNIKE I RAČUNARSTVA STRUKOVNIH STUDIJA-VIŠER, BEOGRAD
STUDIJSKI PROGRAM: NET
PREDMET: Električni Pretvarači Snage 2021

PRIMER DIMENZIONISANJA DC-DC SPUŠTAČA NAPONA





PREDMETNI PROFESOR:
DR ŽELJKO DESPOTOVIĆ, DIPL.EL.INŽ.

OSNOVNA KONFIGURACIJA TOPOLOGIJE

Continuous Conduction Mode (CCM)

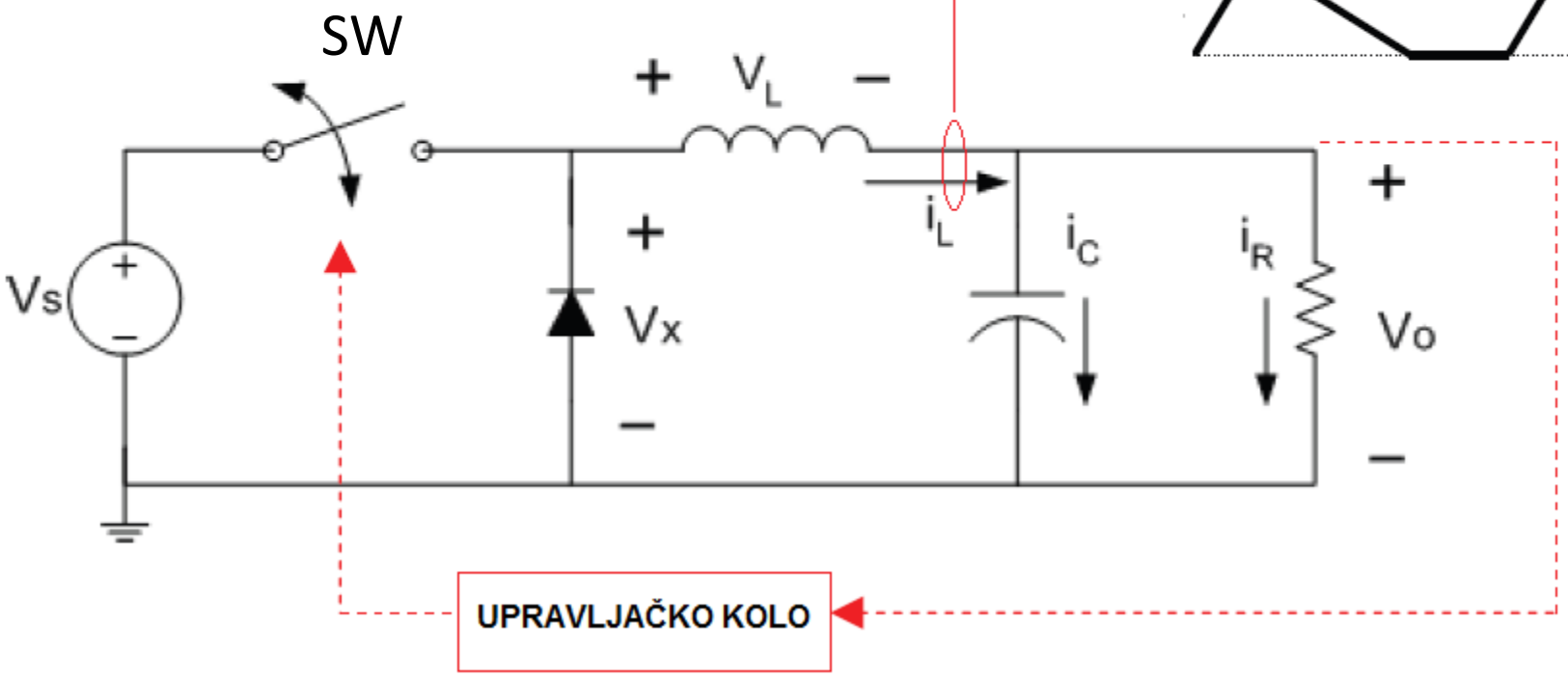
KONTINUALNI REŽIM RADA

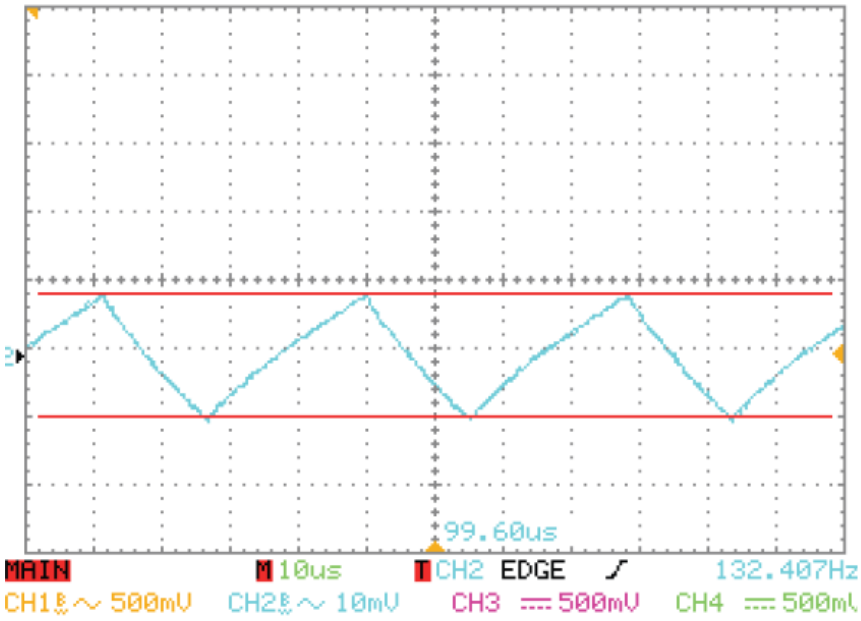
CCM

Discontinuous Conduction Mode (DCM)

DISKONTINUALNI REŽIM RADA

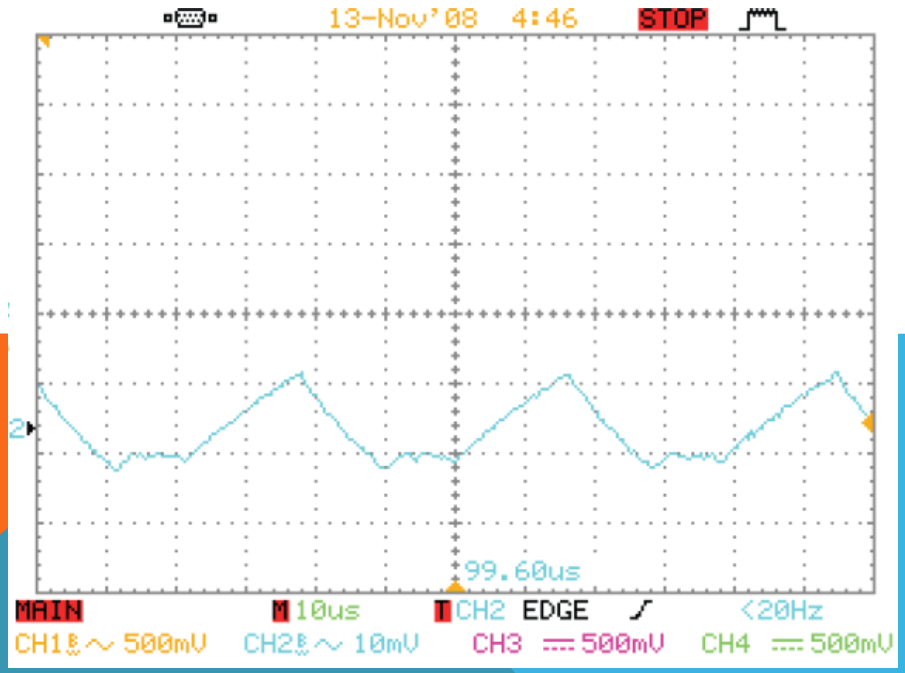
DCM





KAKO TO IZGLEDA U STVARNOSTI?

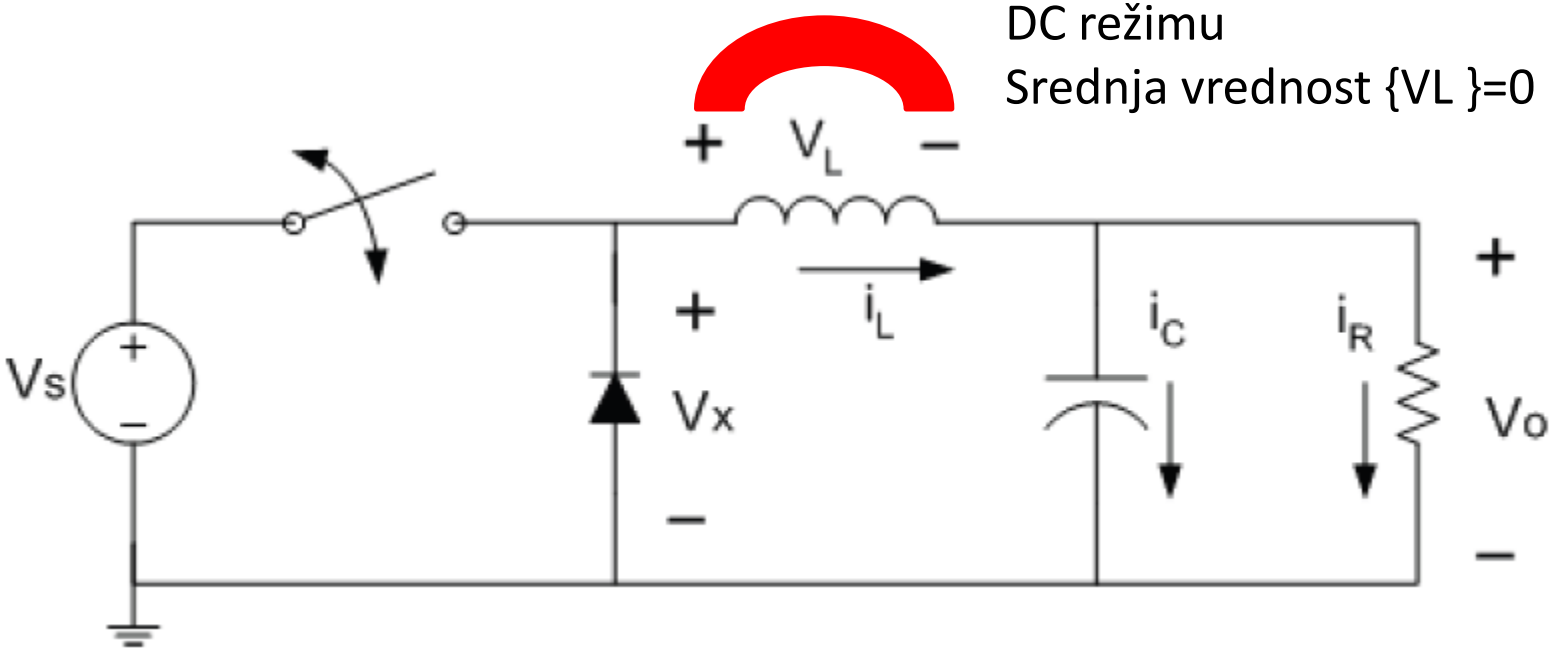
CCM režim
ili KONTINUALNI



DCM režim
ili DISKONTINUALNI

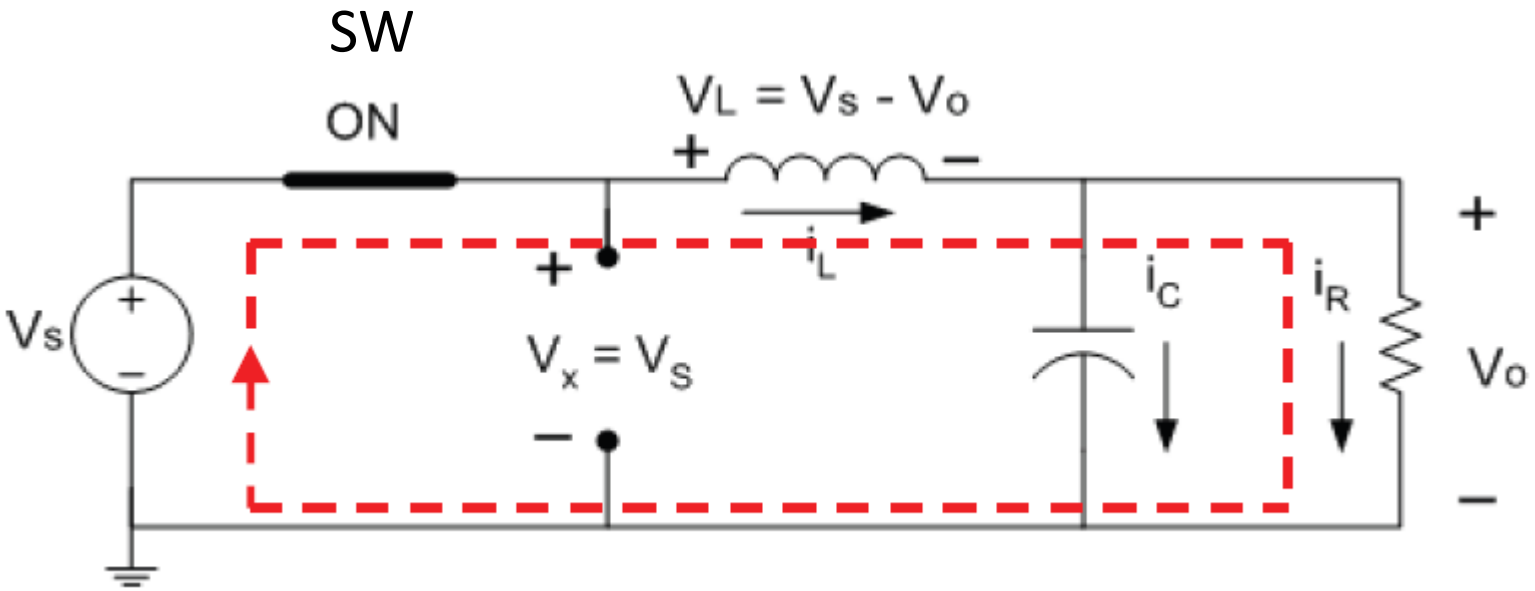
Induktivnost je KRATAK SPOJ u DC režimu

Srednja vrednost {VL }=0



$$\overline{V_L} = v_{Lon} t_{on} + v_{Loff} t_{off} = 0$$

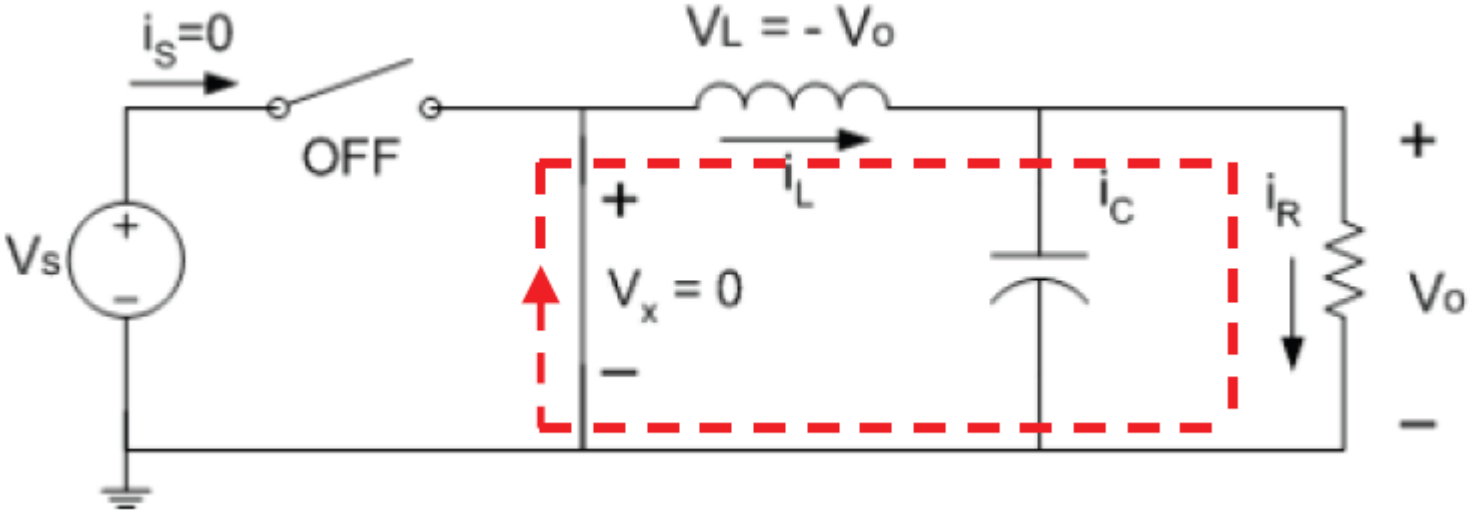
Prekidač SW zatvoren (režim u intervalu ton)



$$v_{Lon} = V_S - V_O$$

$$D = t_{on}/T$$

Prekidač SW otvoren (režim u intervalu toff)



$$v_{Loff} = -V_O$$

$$t_{off} = T - t_{on} = T - DT$$

$$t_{off} = (1-D)T$$

Prenosna funkcija pretvarača u ustaljenom režimu u modu CCM

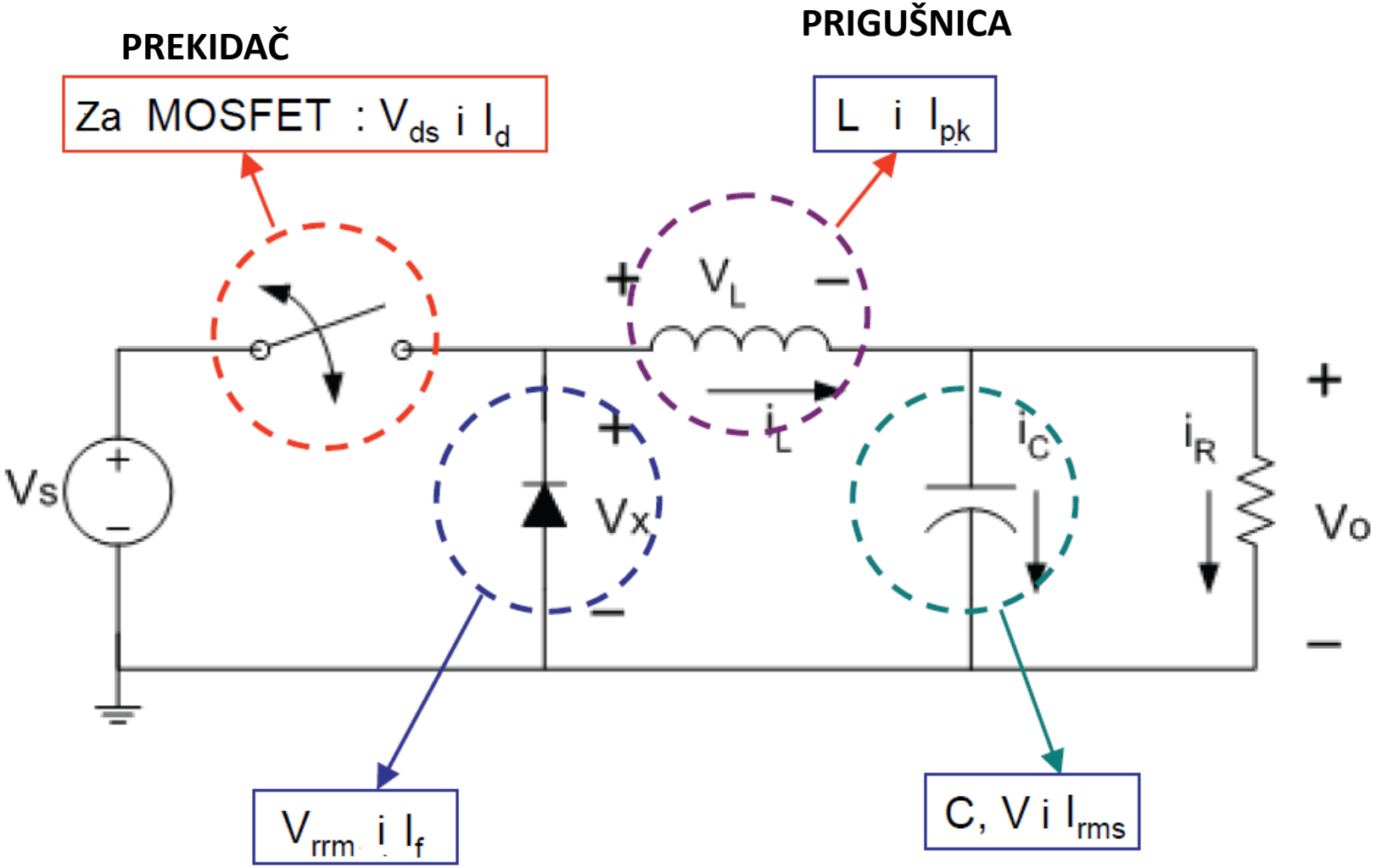
$$v_{Lon}t_{on} + v_{Loff}t_{off} = 0$$

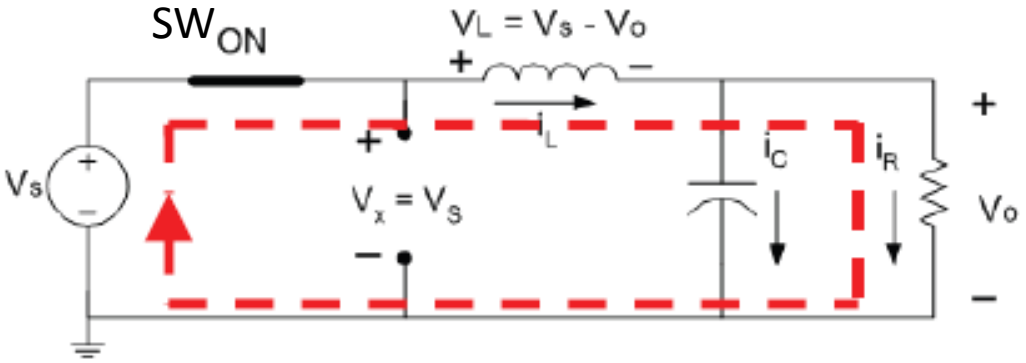
$$(V_S - V_O)DT + (-V_O)(1-D)T = 0$$

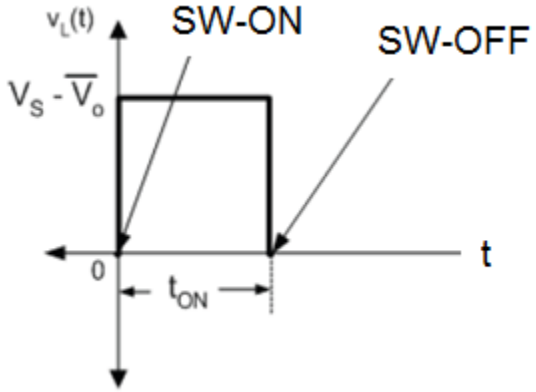
$$V_S D - V_O D - V_O + V_O D = 0$$

$$\boxed{V_O = DV_S}$$

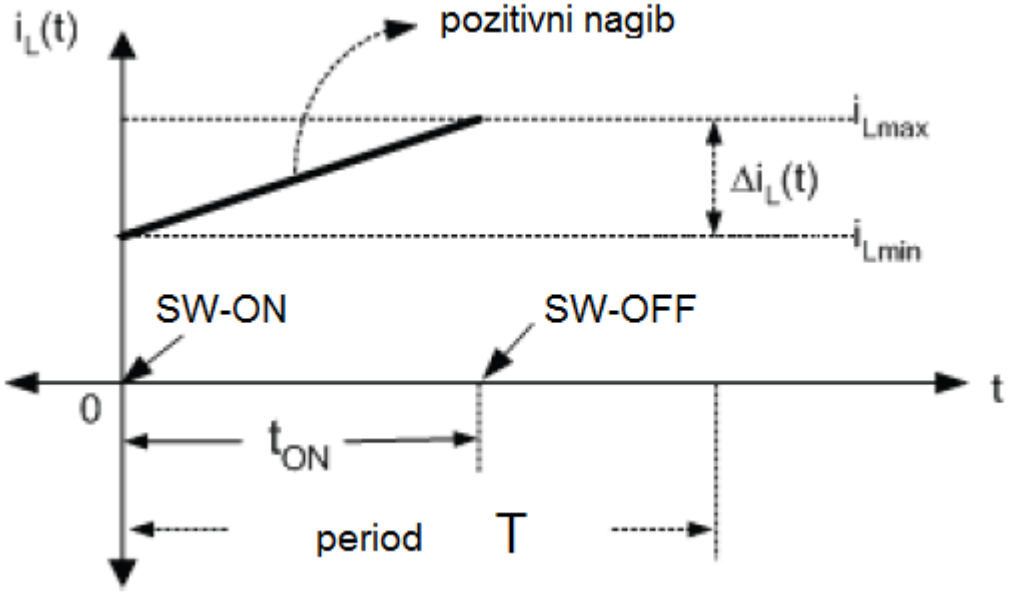
DIMENZIONISANJE PRETVARAČA (Šta se ustvari dimenzioniše?)





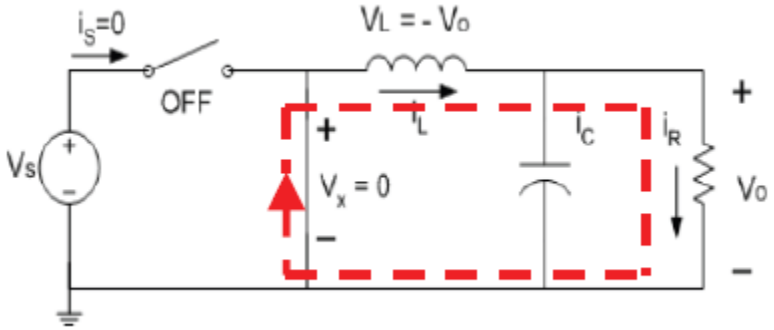


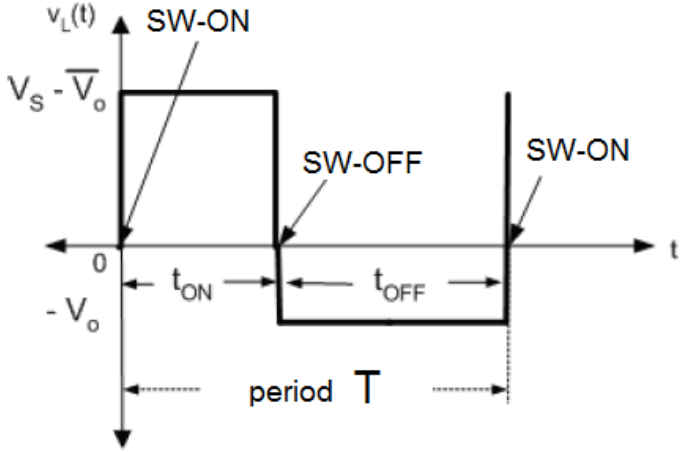
$$v_L = V_S - V_O = L\frac{di_L}{dt} \quad \Rightarrow \quad \frac{di_L}{dt} = \frac{V_S - V_O}{L} = \oplus$$



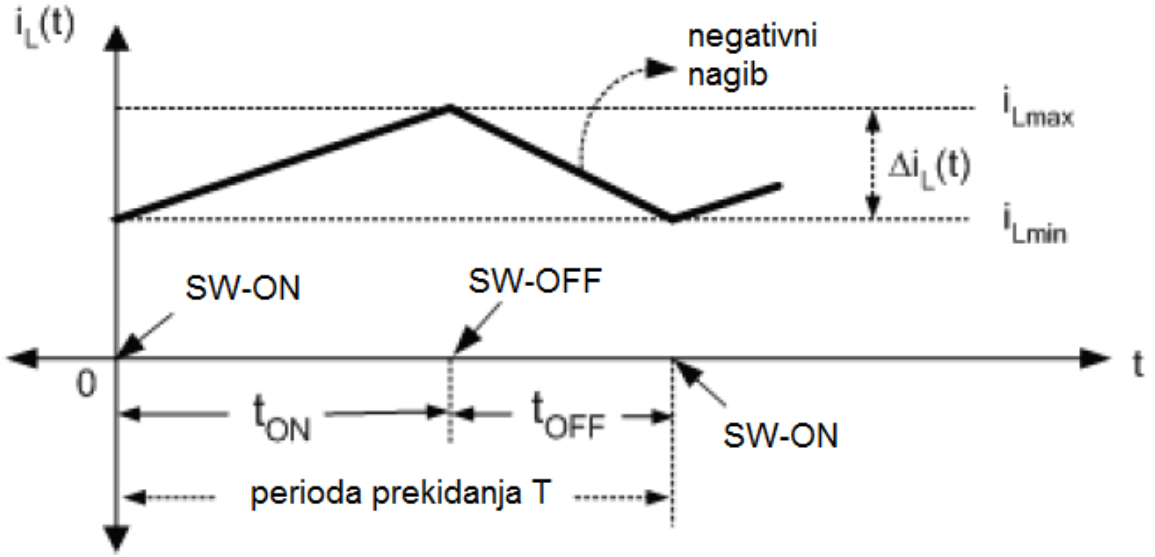
$$\Delta i_{Lon} = \frac{V_S - V_O}{L}\Delta t_{on}$$

$$\Delta i_{Lon} = \frac{V_S - V_O}{L} DT$$



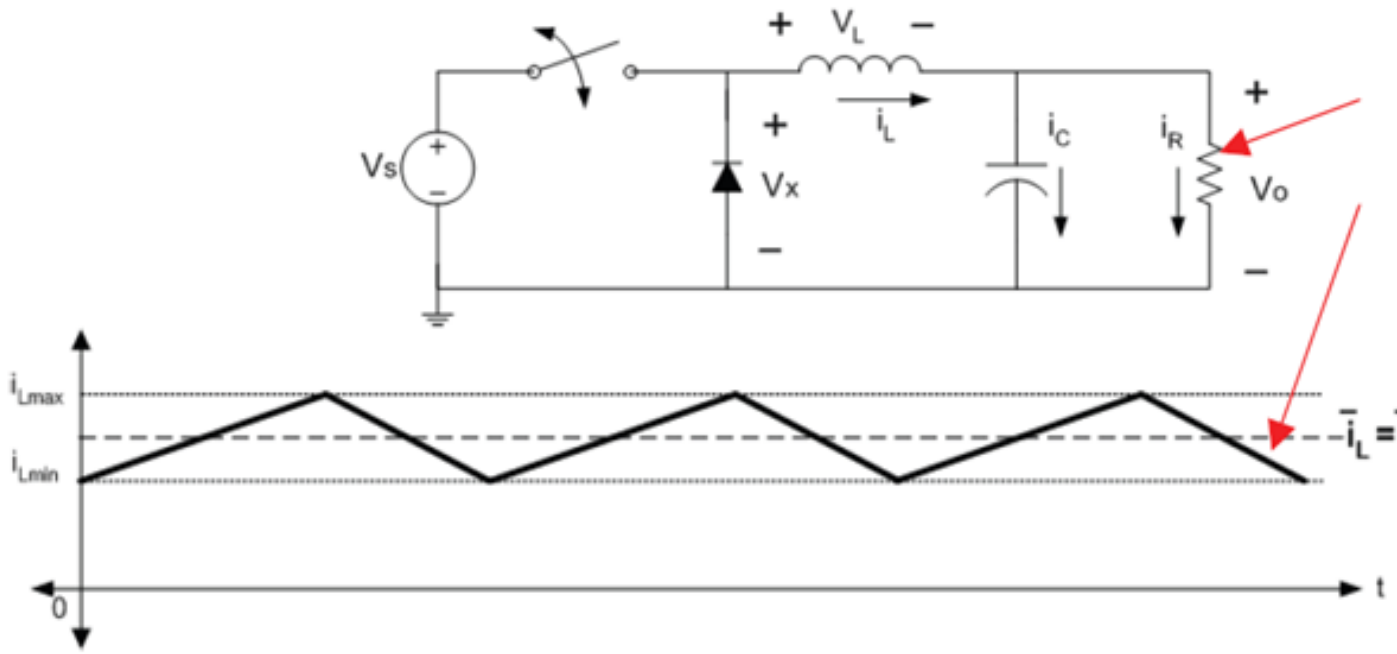


$$v_L = -V_O = L\frac{di_L}{dt} \quad \Rightarrow \quad \frac{di_L}{dt} = \frac{-V_O}{L} = \boxed{-}$$



$$\Delta i_{Loff} = \frac{-V_O}{L}\Delta t_{off}$$

$$\Delta i_{Loff} = \frac{-V_O}{L}(1-D)T$$

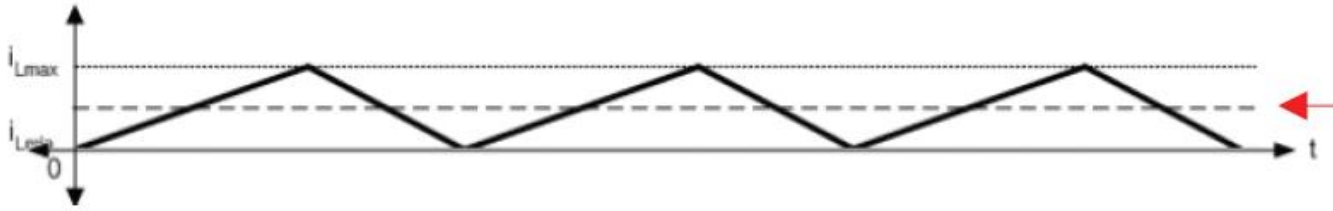


srednja vrednost stuje prigušnice je jednaka srednjoj vrednosti izlazne struje Vo/R

$$I_{L\min} = \overline{I_L} - \frac{|\Delta i_L|}{2} = \frac{V_0}{R} - \frac{1}{2}\left[\frac{V_0}{L}(1-D)T\right] = V_0\left[\frac{1}{R} - \frac{(1-D)}{2Lf}\right]$$

$$I_{L\max} = \overline{I_L} + \frac{|\Delta i_L|}{2} = \frac{V_0}{R} + \frac{1}{2}\left[\frac{V_0}{L}(1-D)T\right] = V_0\left[\frac{1}{R} + \frac{(1-D)}{2Lf}\right]$$

DIMENZIONISANJE PRIGUŠNICE



Minimalna struja opterećenja u CCM režimu

$I_{omin}=\Delta i/2$

$L = L_C \quad I_{Lmin} = 0$ praktično $L > 1.05 * L_C$

$$I_{L\min} = 0 = \overline{I_L} - \frac{|\Delta i_L|}{2} = V_0 \left[\frac{1}{R_{\max}} - \frac{(1-D)}{2 L_C f} \right] \Rightarrow L_C = \frac{(1-D_{\max}) R_{\max}}{2 f}$$

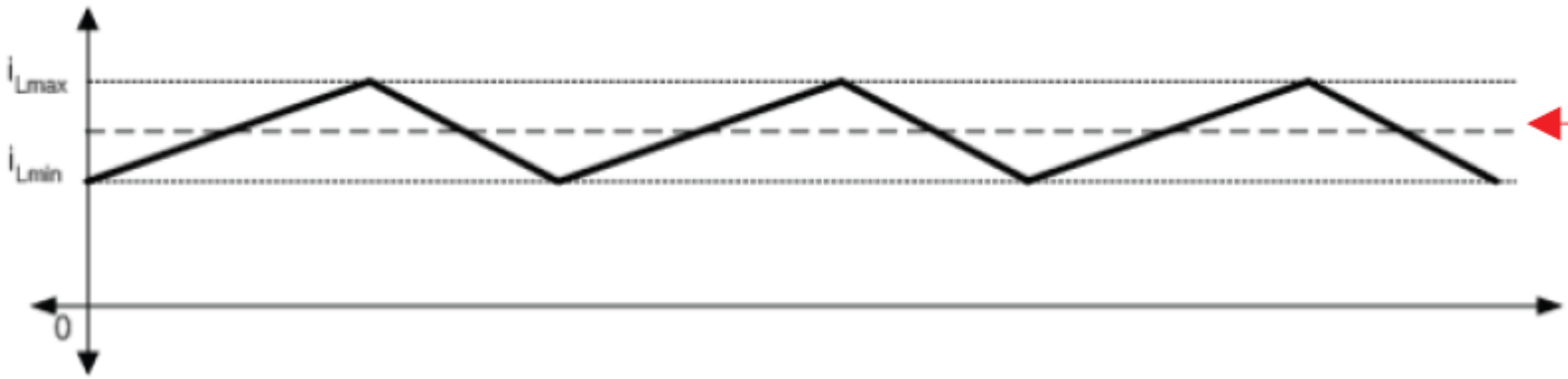
$$L_C = \frac{(1-D_{\max}) R_{\max}}{2 f}$$

$R_{max} = V_o/I_{omin}$

Pri MIN ulaznom naponu

Izbor projektanta (UGLAVNOM JE >50KHz kod upotrebe MOSFET'a)

ODREĐIVANJE MAX STRUJE PRIGUŠNICE



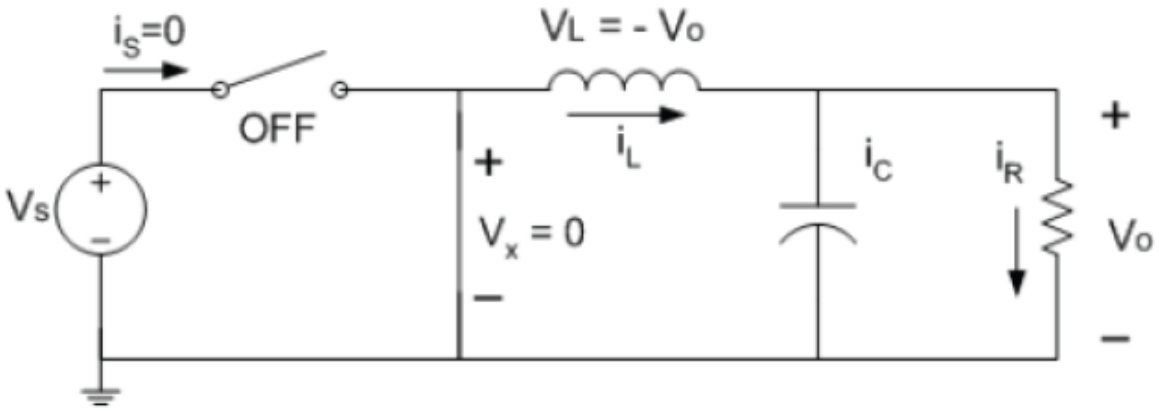
MAX struja opterećenja

$$I_{L\max} = \overline{I}_L + \frac{|\Delta i_L|}{2} = V_0 \left[\frac{1}{R_{\min}} + \frac{(1 - D_{\min})}{2Lf} \right]$$

Pri MAX ulaznom naponu

$L > 1.05 * L_C$

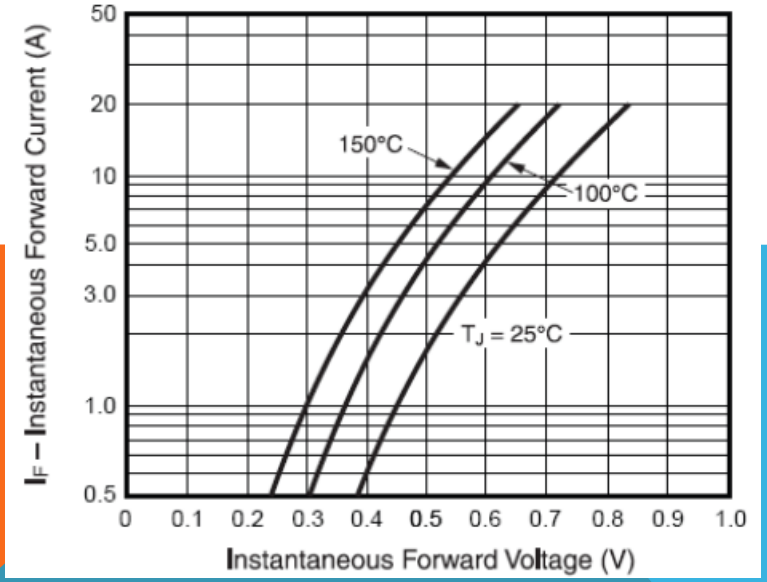
DIMENZIONISANJE PREKIDAČA -SW



U ISKLJUČENOM STANJU
PREKIDAČ (SW)
TRPI NAJVEĆI NAPON

AKO JE DIODA IDEALNA: $V_{switch\text{-}max} = V_{inmax}$

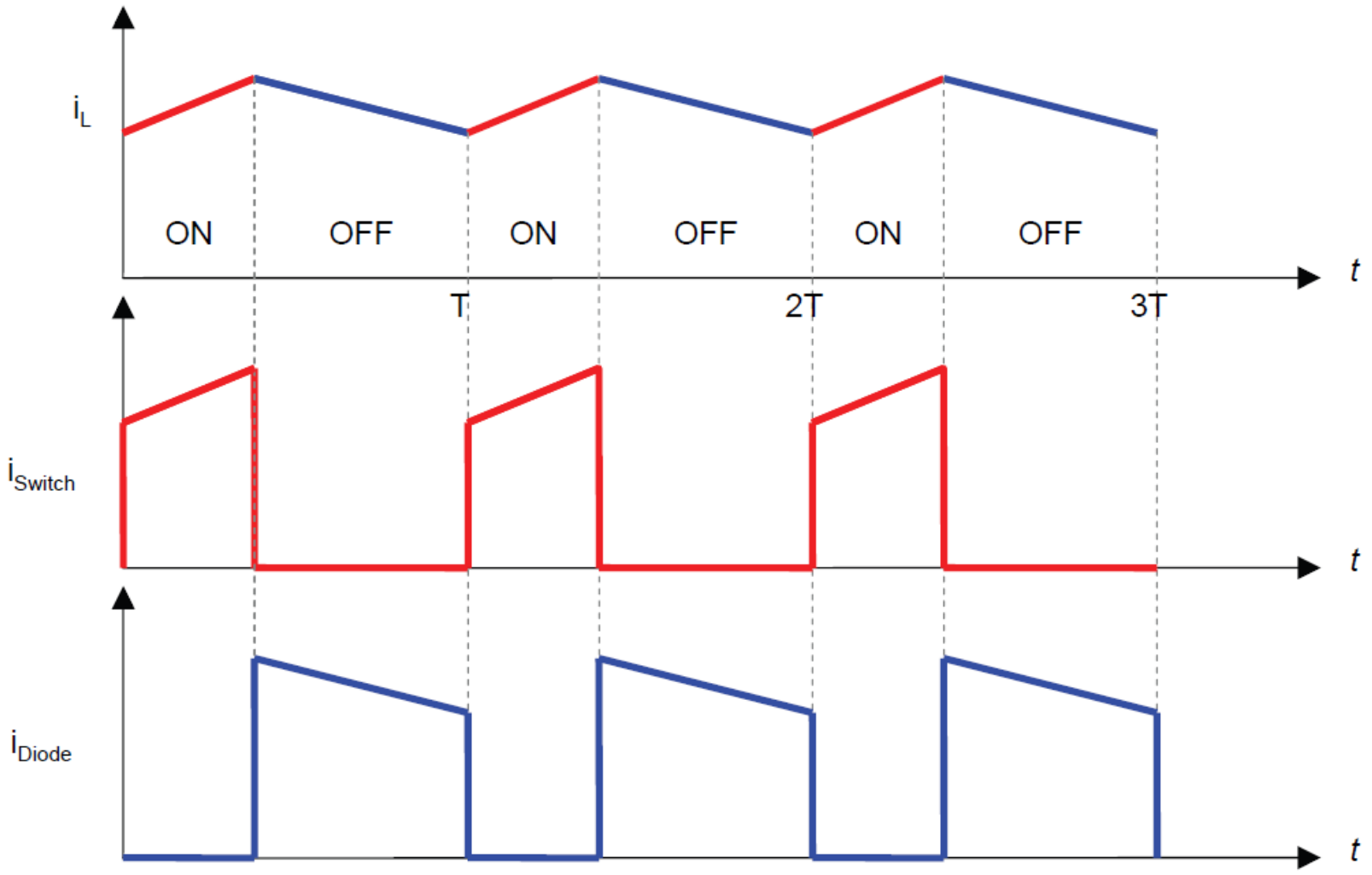
AKO DIODA NIJE IDEALNA: $V_{switch\text{-}max} = V_{inmax} + V_F$

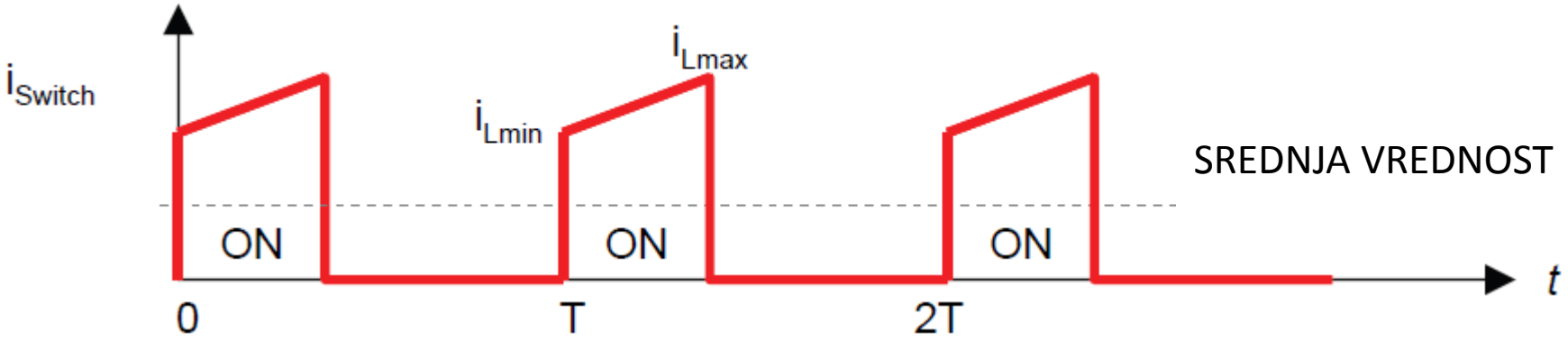


KARAKTERISTIKA
TIPIČNE DIODE

ZA NAPON PREKIDAČA Vds SE USVAJA 20% VEĆI NAPON OD $V_{sw\text{-}max}$!!!!!

STRUJA PREKIDAČA ?





SREDNJA VREDNOST

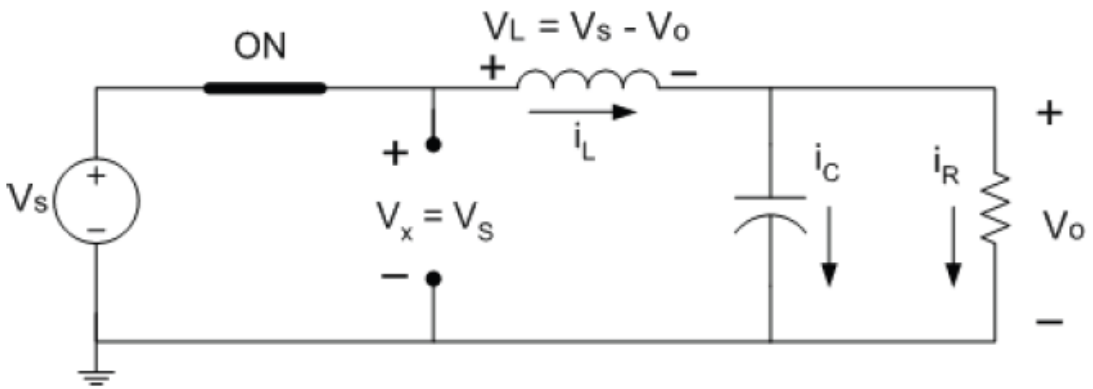
$$\overline{I_{Switch}} = \frac{\left(i_{L\min} + i_{L\max}\right)\cdot t_{on}}{2\cdot T}$$

$$\overline{I_{Switch}} = \frac{\left(\left[i_{L\max} - \Delta i_L\right] + i_{L\max}\right)\cdot DT}{2\cdot T} = \frac{\left(2i_{L\max} - \Delta i_L\right)\cdot D}{2}$$

$$\overline{I_{Switch}} = \left(i_{L\max} - \frac{\Delta i_L}{2}\right) D = \overline{I_L}\cdot D = \overline{I_o}\cdot D$$

$$\overline{I_{Switch-\max}} > \overline{I_{o\max}}\cdot D_{\max}$$

DIMENZIONISANJE DIODE (obično je to Šotki dioda)



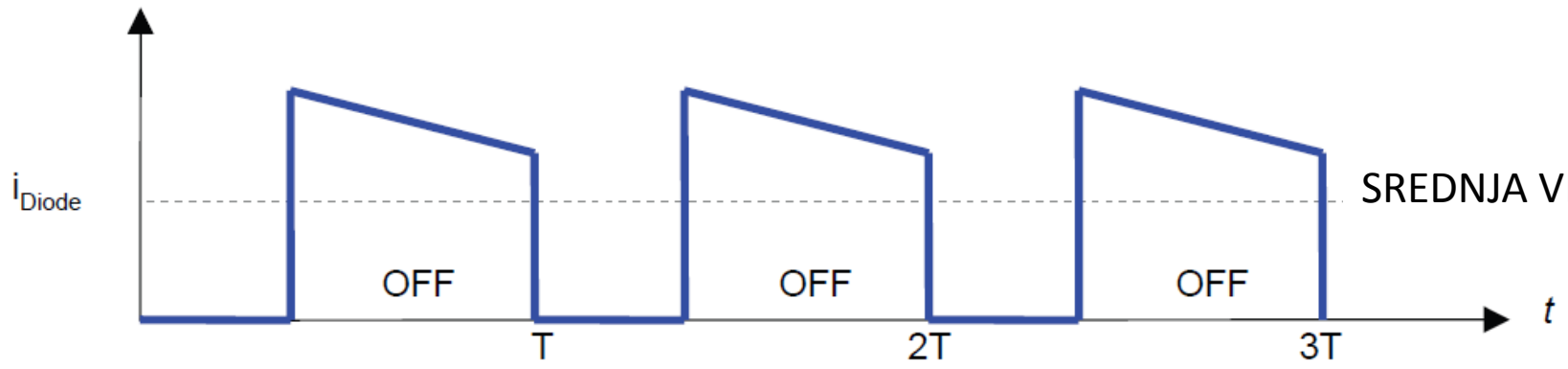
Kada je SW uključen
dioda trpi INVERZNI NAPON !!

KADA JE PREKIDAČ IDEALAN: $V_{RRM} = V_{inmax}$

KADA PREKIDAČ NIJE IDEALAN: $V_{RRM} = V_{inmax} + V_{SW}$

ZA NAPON DIODE SE USVAJA minimum 20%
VEĆI NAPON OD V_{RRM}!!!!!

STRUJA DIODE ?



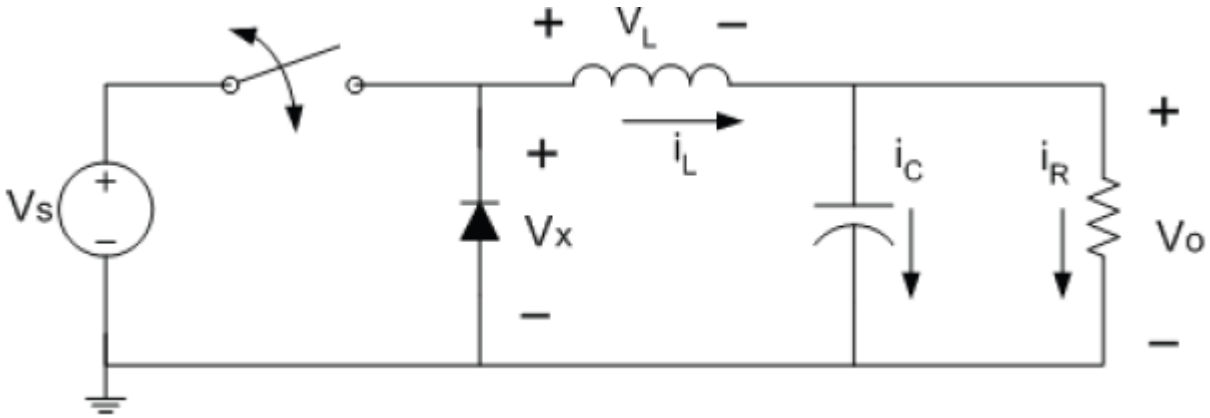
$$\overline{I_F} = \frac{\left(i_{L\min} + i_{L\max}\right)\cdot t_{off}}{2\cdot T}$$

$$\overline{I_F} = \frac{\left(\left[i_{L\max} - \Delta i_L\right] + i_{L\max}\right)\cdot\left(1-D\right)T}{2\cdot T} = \frac{\left(2i_{L\max} - \Delta i_L\right)\cdot\left(1-D\right)}{2}$$

$$\overline{I_F} = \overline{I_L}\cdot\left(1-D\right) = \overline{I_o}\cdot\left(1-D\right)$$

$$\overline{I_F} > \overline{I_{o\max}}\cdot\left(1-D_{\min}\right)$$

DIMENZIONISANJE KONDENZATORA



$$V_{cmax} = V_o + \Delta V_o/2$$

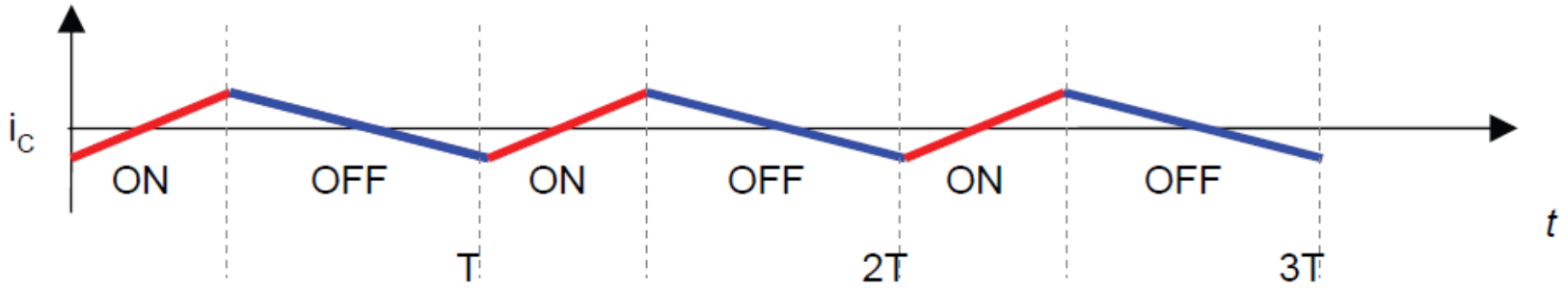
ESR (Equivalent Series Resistance)

-utiče na dodatno povećanje ripla napona ΔV_o

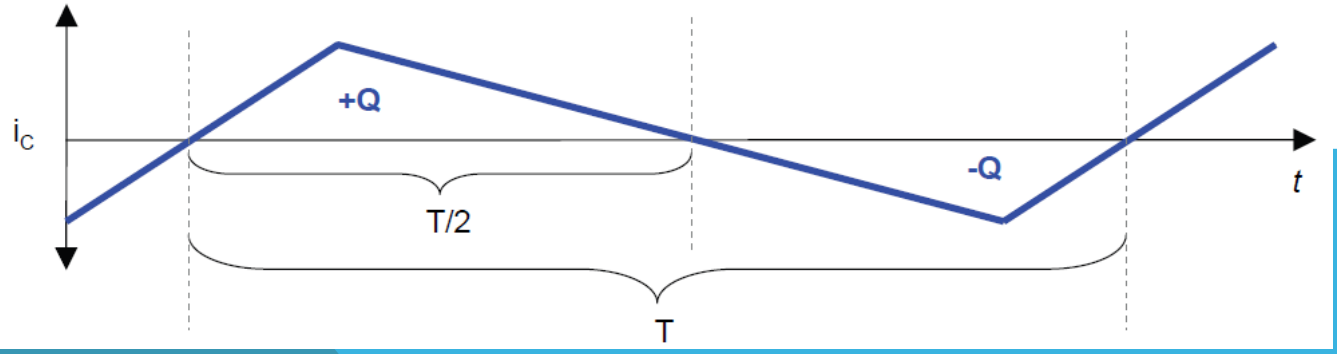
-dodatno povećanje ripla napona: $ESR * \Delta I_L$

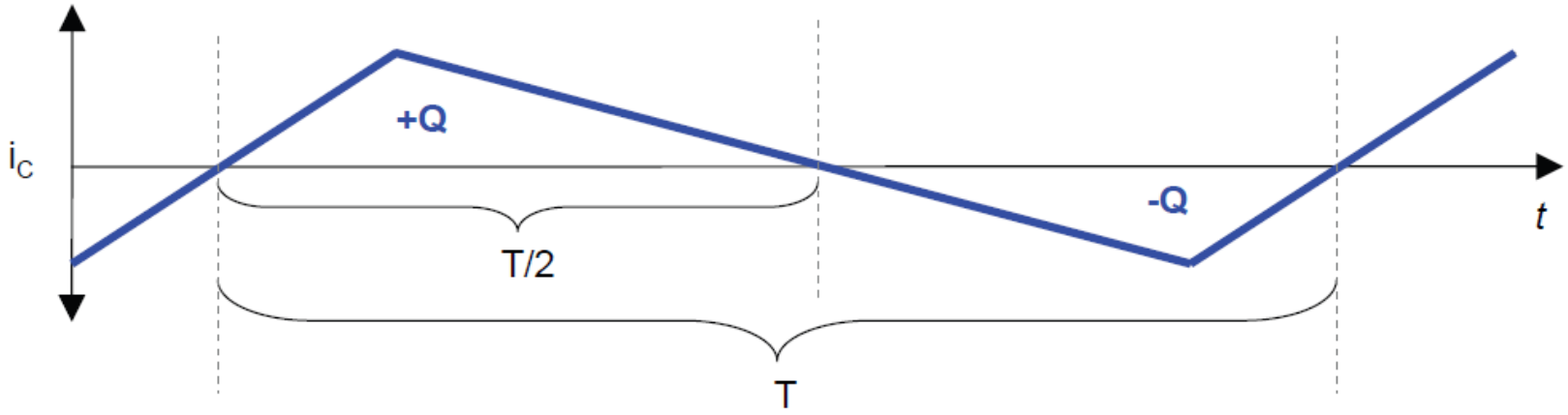
Težnja je da ESR bude što manje , kao i talasnost struje !!!!

KAKO PRORAČUNATI MIN KAPACITIVNOST?



Kroz kondenzator protiče AC(naizmenična) komponenta struje prigušnice





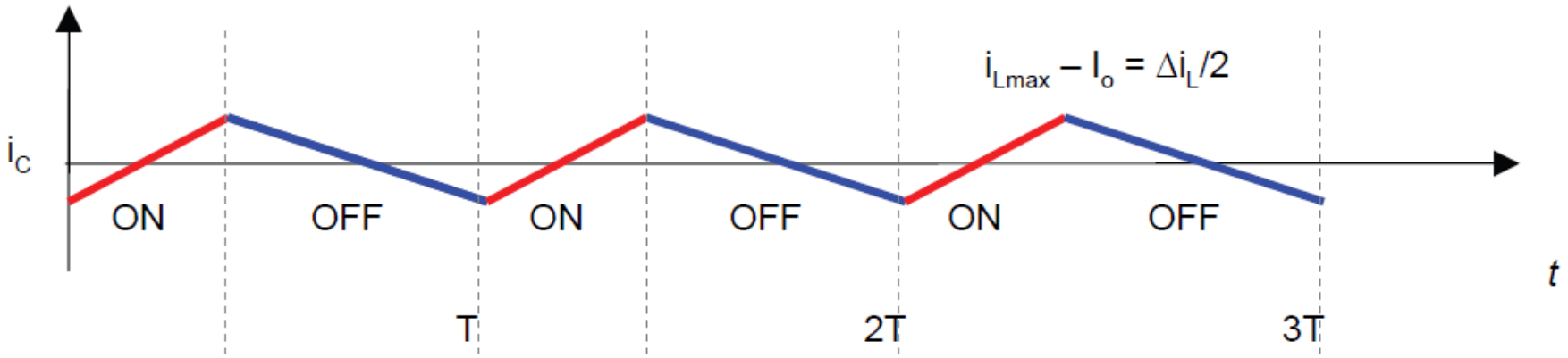
$$q = \mathrm{P}_{\Delta} = \frac{1}{2}\left(\frac{T}{2}\right)\left(\frac{\Delta i_L}{2}\right) = \frac{\Delta i_L}{8f} = \frac{\frac{V_O}{L}(1-D)T}{8f} = \frac{(1-D)V_O}{8Lf^2}$$

$$q = C \cdot \Delta V_o \Rightarrow C = \frac{q}{\Delta V_o} = \frac{(1-D)V_O}{8Lf^2\Delta V_o} = \frac{(1-D)}{8Lf^2\left(\Delta V_o / V_O\right)}$$

$$C = \frac{\left(1-D_{\min}\right)}{8Lf^2\left(\Delta V_o / V_O\right)}$$

RELATIVNA VREDNOST TALASNOSTI (tzv.RIPLA) NAPONA (izraženo u r.j.)

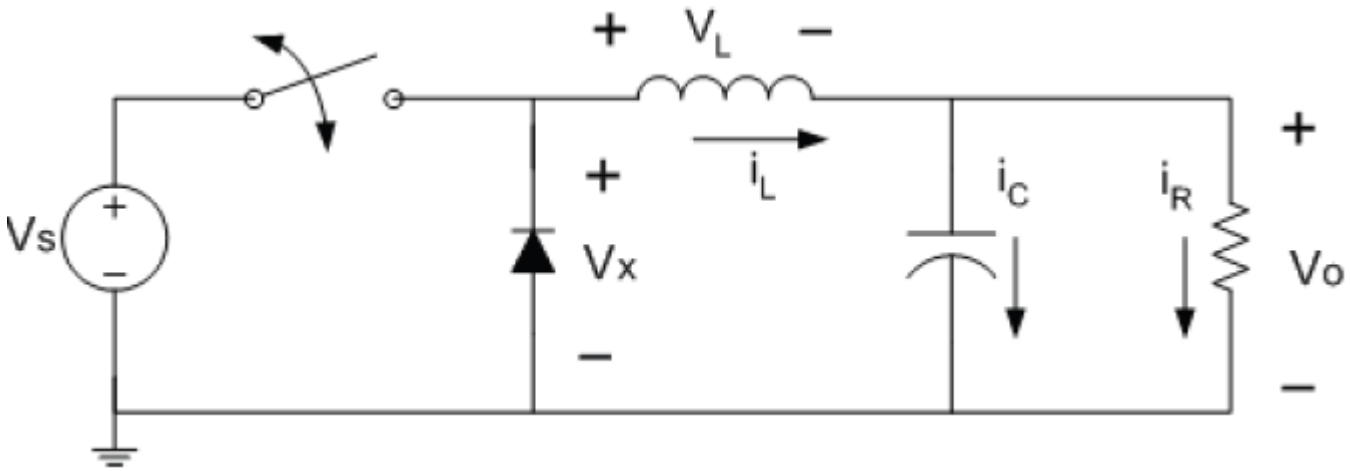
EFEKTIVNA VREDOST STRUJE KONDENZATORA?



$$i_{Crms} = \frac{i_{Cpk}}{\sqrt{3}} = \frac{\Delta i_L/2}{\sqrt{3}} = \frac{(1-D)V_O}{2\sqrt{3}Lf}$$

$$i_{Crms} = \frac{(1-D_{\min})V_O}{2\sqrt{3}Lf}$$

MAX NAPON KONDENZATORA ?



$$V_{cmax} = V_{inmax} \ ?$$

Kada je D=1 (prekidač je dovoljno dugo uključen) Vc=Vin

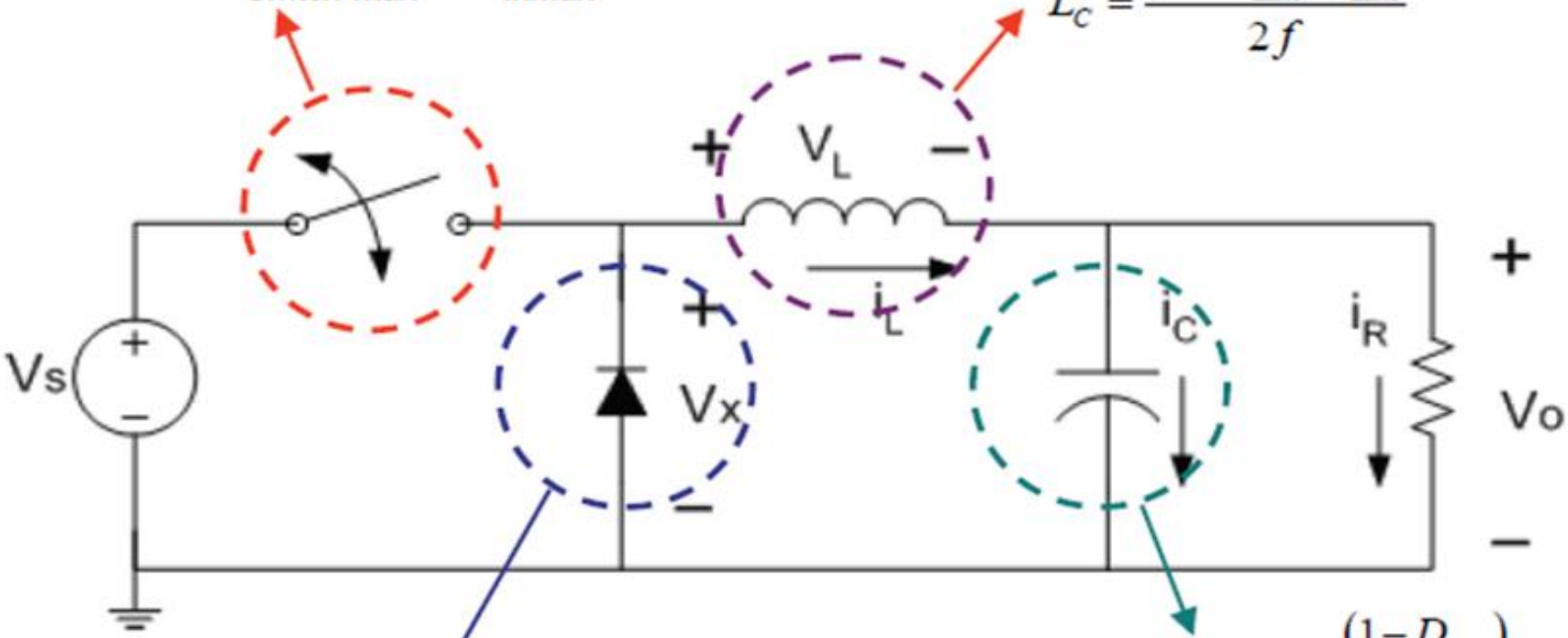
SUMARNO:

$$\overline{I_{Switch-\max}} > \overline{I_{o\max}} \cdot D_{\max}$$

$V_{switch\text{-}max} = V_{inmax}$

$$I_{L\max} = V_0 \left[\frac{1}{R_{\min}} + \frac{(1-D_{\min})}{2Lf} \right]$$

$$L_C = \frac{(1-D_{\max})R_{\max}}{2f}$$



$$\overline{I_F} > \overline{I_{o\max}} \cdot (1-D_{\min})$$

$V_{RRM} = V_{inmax}$

$$C = \frac{(1-D_{\min})}{8Lf^2(\Delta V_o/V_o)}$$

$V_{cmax} = V_o + \Delta V_o/2$

$$i_{Crms} = \frac{(1-D_{\min})V_o}{2\sqrt{3}Lf}$$

KAKO UZETI U OBZIR GUBITKE U PRETVARAČU?

Koji sve postoje gubici??

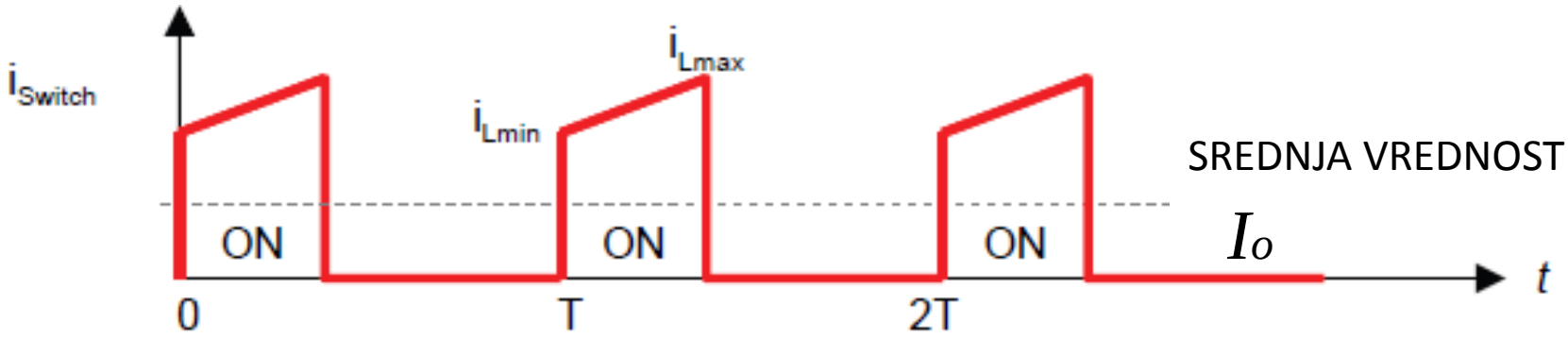
MOSFET:
-Statički gubici u MOSFET prekidaču
-Prekidački dinamičkigubici u MOSFET prekidaču
-Gubici u pobudnom kolu MOSFET prekidača

DIODA:
-Statički gubici
-Prekidački gubici

PRIGUŠNICA:
-gubici u bakru
-gubici u gvožđu

KONDENZATOR:
-gubici u ekvivalentnoj serijskoj otpornosti (ESR)

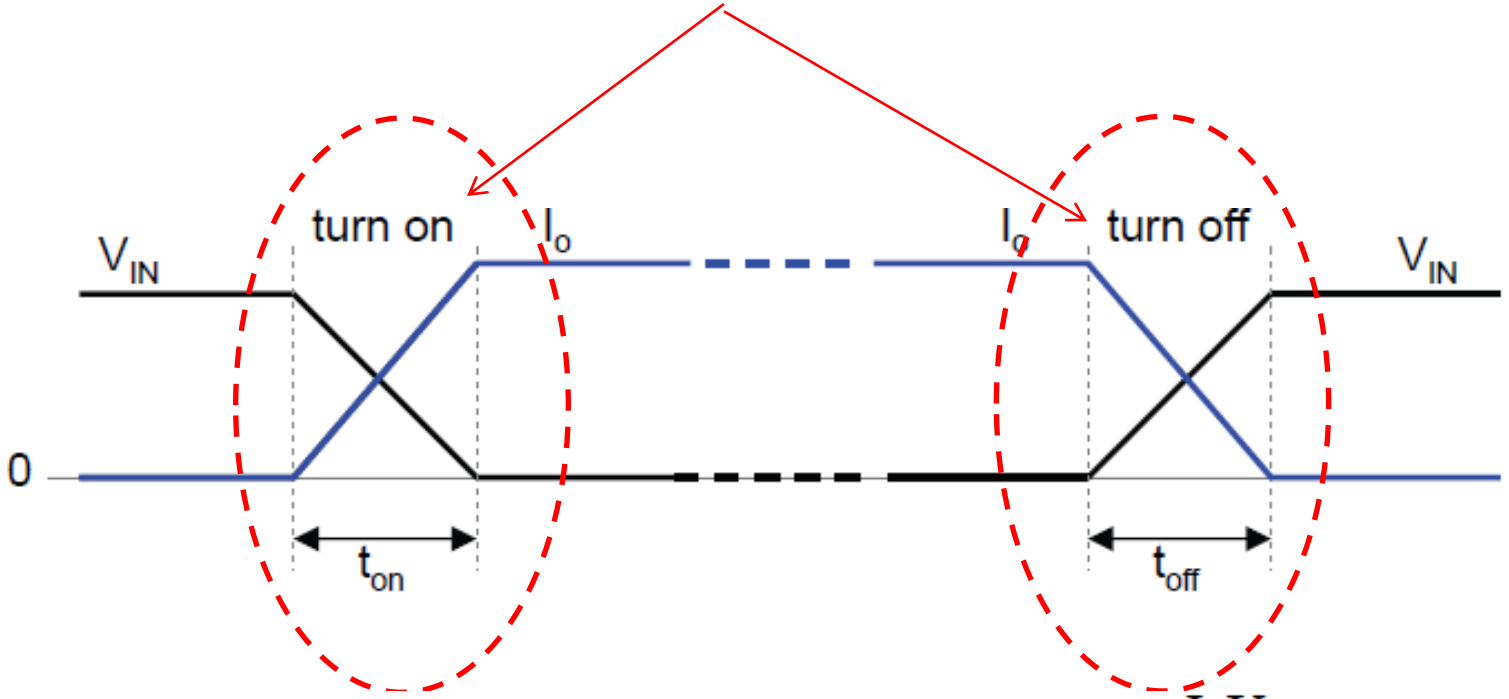
STATIČKI GUBICI MOSFET PREKIDAČA



$$P_{static} = I^2_{switch-rms} \cdot R_{DSon}$$

$$P_{static} = \left(I_o \sqrt{D} \sqrt{\left(1 + \left[\frac{\Delta i_L}{2 \cdot I_o} \right] \right)} \right)^2 \cdot R_{DSon}$$

DINAMIČKI GUBICI MOSFET PREKIDAČA



$$P(t_{on}) = \frac{I_o V_{in} t_{on}}{6T} \qquad P(t_{off}) = \frac{I_o V_{in} t_{off}}{6T}$$

$$P_{switching} = P(t_{on}) + P(t_{off}) = \frac{I_o V_{in} t_{on}}{6T} + \frac{I_o V_{in} t_{off}}{6T}$$

$$P_{switching} = \frac{I_o V_{in}}{6T}\left(t_{on} + t_{off}\right)$$

PREKIDAČKI GUBICI U POBUDNOM KOLU MOSFET PREKIDAČA

KADA JE MOSFET ISKLJUČEN, PUNI SE KAPACITIVNOST Coss:

$$P_{Coss} = \frac{1}{2} C_{OSS} V_{in}^2 f$$

PREKIDAČKI GUBICI U KOLU GEJTA:

$$P_{gate} = \frac{1}{2} Q_{gate} V_{gate} f$$

STATIČKI GUBICI DIODE U STANJU PROVOĐENJA

$$P_{forward} = V_f \cdot \overline{I_f} + \widetilde{I_f^2} \cdot r_d$$

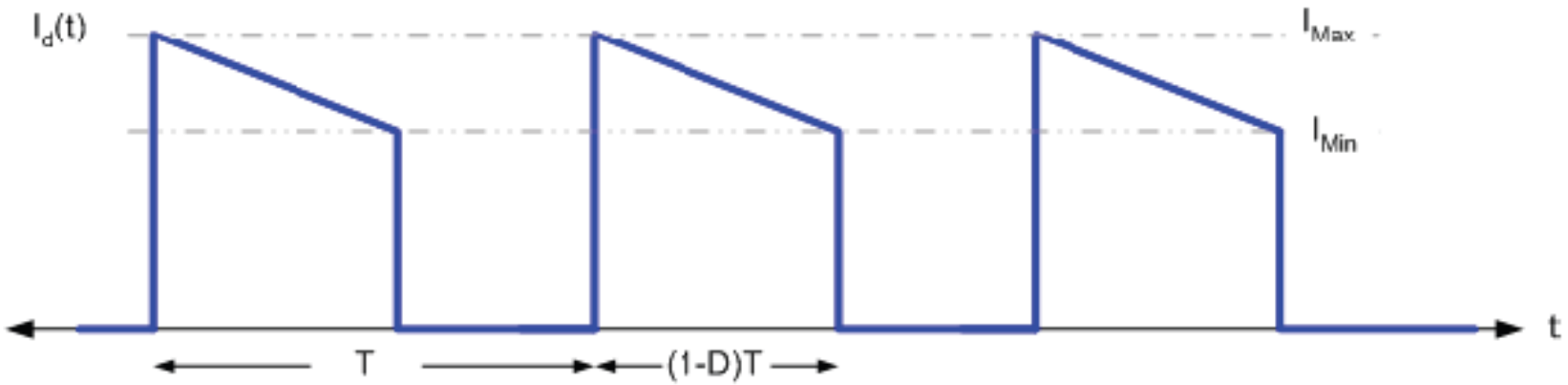
* PAD NAPONA U STANJU VOĐENJA

SREDNJA VREDNOST STRUJE DIODE

EFEKTIVNA VREDNOST STRUJE DIODE

DINAMIČKA OTPORNOST DIODE *

* KATALOG PROIZVOĐAČA



IZ KATALOGA PROIZVOĐAČA

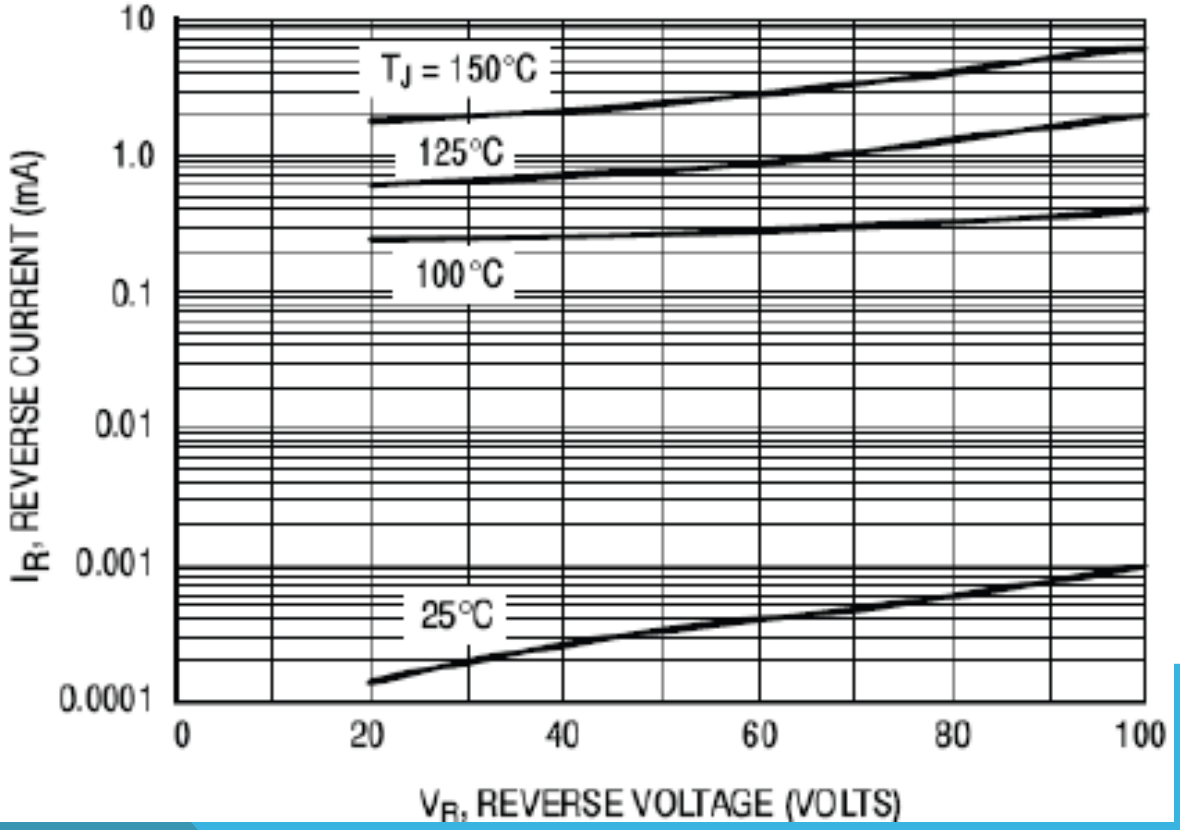
$$P_{forward} = V_f \cdot \overline{I_f} + \widetilde{I_f^2} \cdot r_d$$

$$\overline{I_f} = (1-D) \cdot \overline{I_o}$$

$$\widetilde{I_f} = \sqrt{\frac{(1-D)}{3}\left[I_{\max}^2 + I_{\min}^2 + I_{\max} \cdot I_{\min} \right]}$$

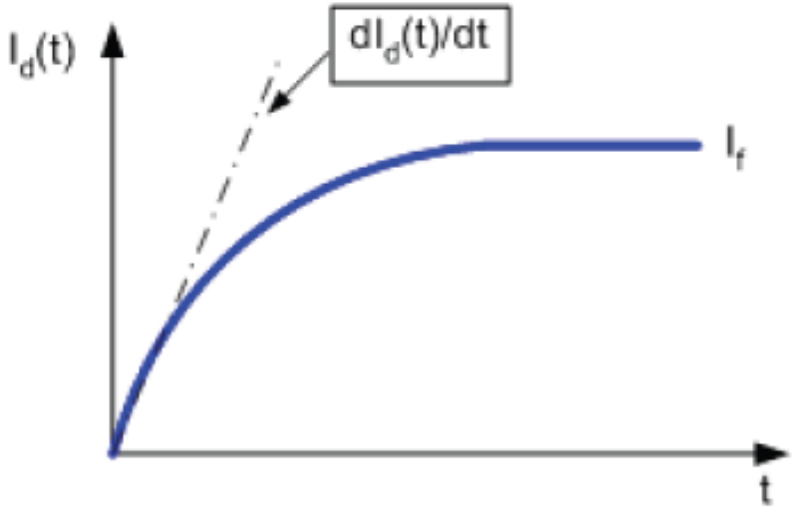
STATIČKI GUBICI DIODE U INVERZNOM REŽIMU (odnosno u STANJU NEPROVOĐENJA)

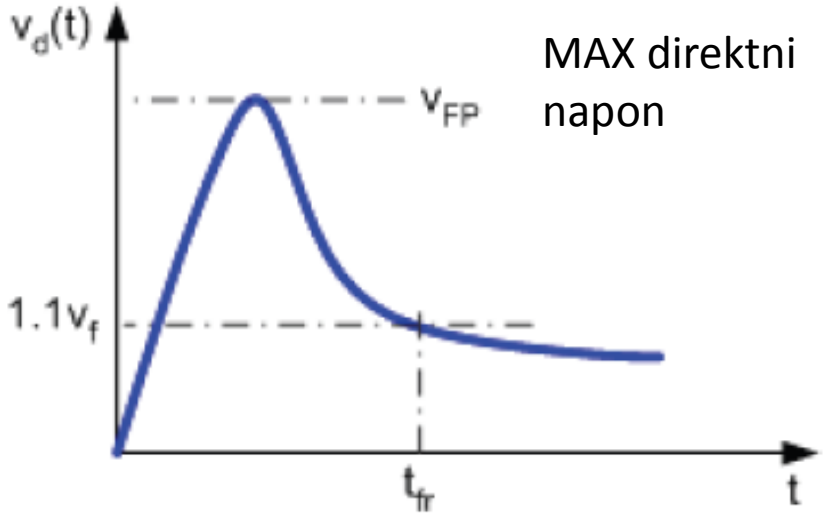
$$P_{reverse} = V_r \cdot I_r \cdot (1 - D)$$



TIPIČNA KARAKTERISTIKA DIODE U INVERZNOM REŽIMU

PREKIDAČKI GUBICI DIODE PRI UKLJUČENJU



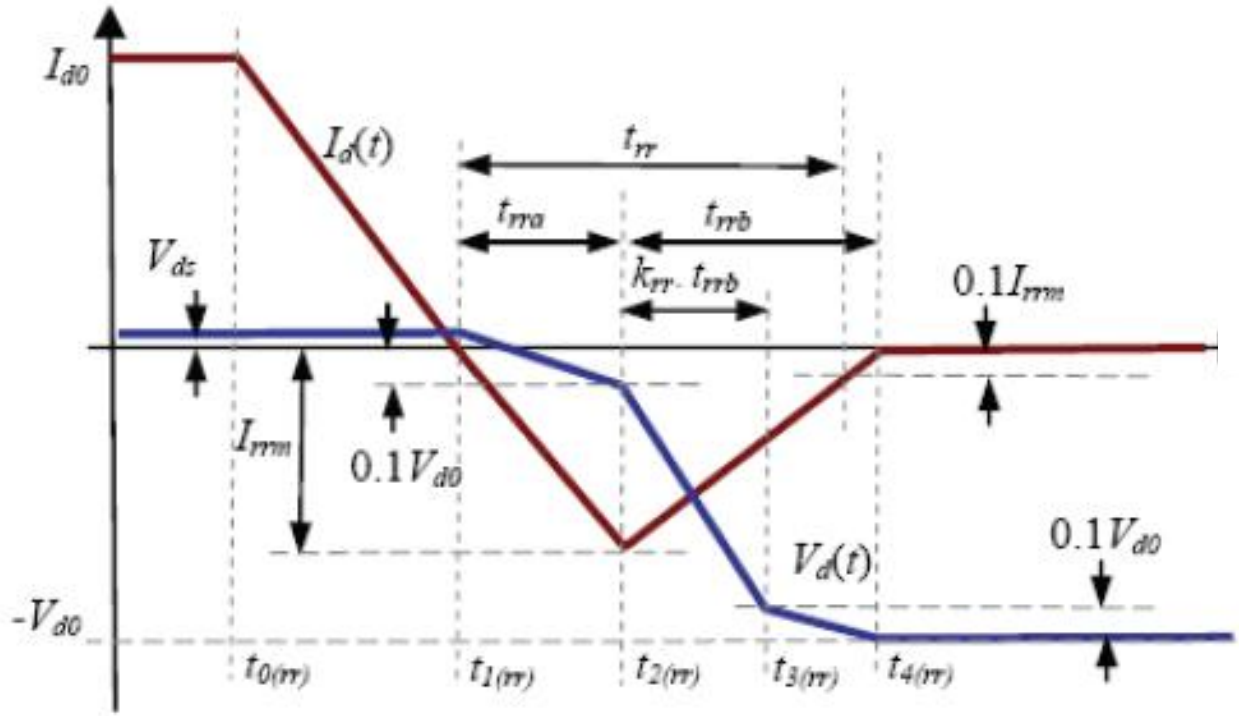


MAX direktni napon

Forwrd Recovery Time

$$P_{ON} = 0.4 \cdot \left(V_{FP} - V_f\right) \cdot t_{fr} \cdot I_f \cdot f$$

PREKIDAČKI GUBICI DIODE PRI ISKLJUČENJU



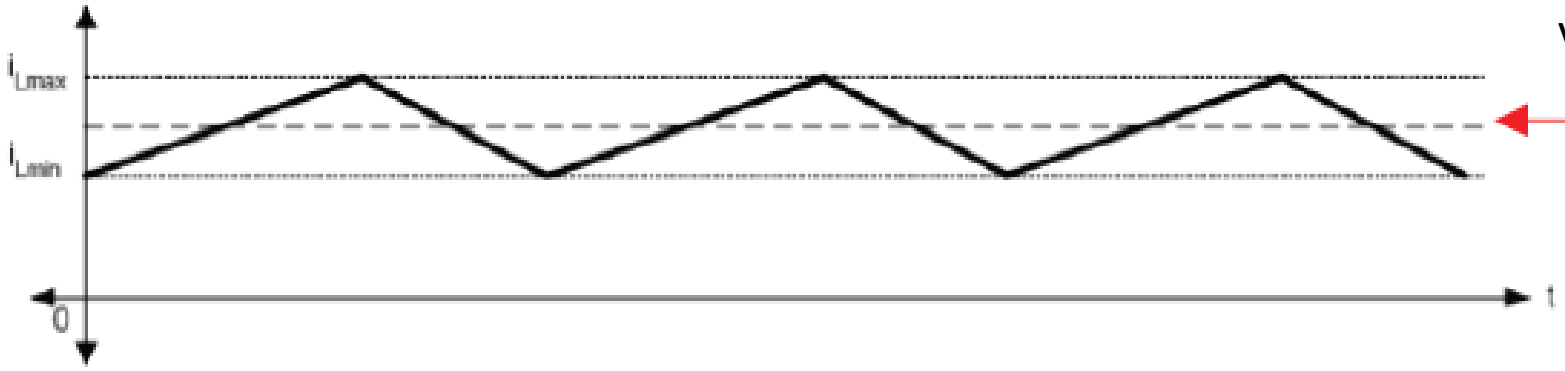
$$t_{rra} = I_{rrm} \Big/ \frac{I_{d0}}{\left(\frac{dI_d}{dt}\Big|_{t_{1(rr)}}\right)}$$

$$t_{rrb} = 1.11 \cdot \left(t_{rr} - t_{rra}\right)$$

$$\left[t_{2rr}, t_{3rr}\right] = k_{rr} \cdot t_{rrb}$$

$$P_{off} = 0.5 V_{ds} I_{d0} \frac{I_{d0}}{\left(\frac{dI_d}{dt}\Big|_{t_{1(rr)}}\right)} + 0.033 V_{d0} I_{rrm} t_{rra} + V_{d0} I_{rrm} \left(0.467 - 0.433 k_{rr} + 0.15 k_{rr}^2\right) t_{rrb}$$

GUBICI u OTPORU INDUKTIVNOSTI (gubici u bakru)



$$P_L = \widetilde{I}_L^{\,2} R_L$$

$$\widetilde{I}_L = I\sqrt{1+\frac{1}{3}\left(\frac{\Delta i_L}{2I}\right)^2}$$

GUBICI u FERITNOM JEZGRU INDUKTIVNOSTI (gubici u gvožđu)

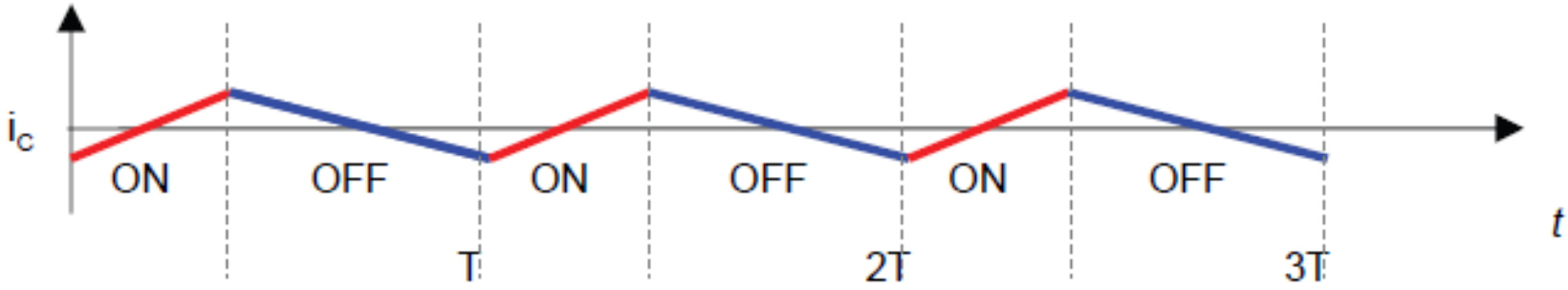
$$= k1 \times B^{k2} \times F^{k3} \times V_{Fe}$$

V_{Fe}- zapremina feritnog jezgra

B- magnetna indukcija u feritnom jezgru (200mT-500mT)

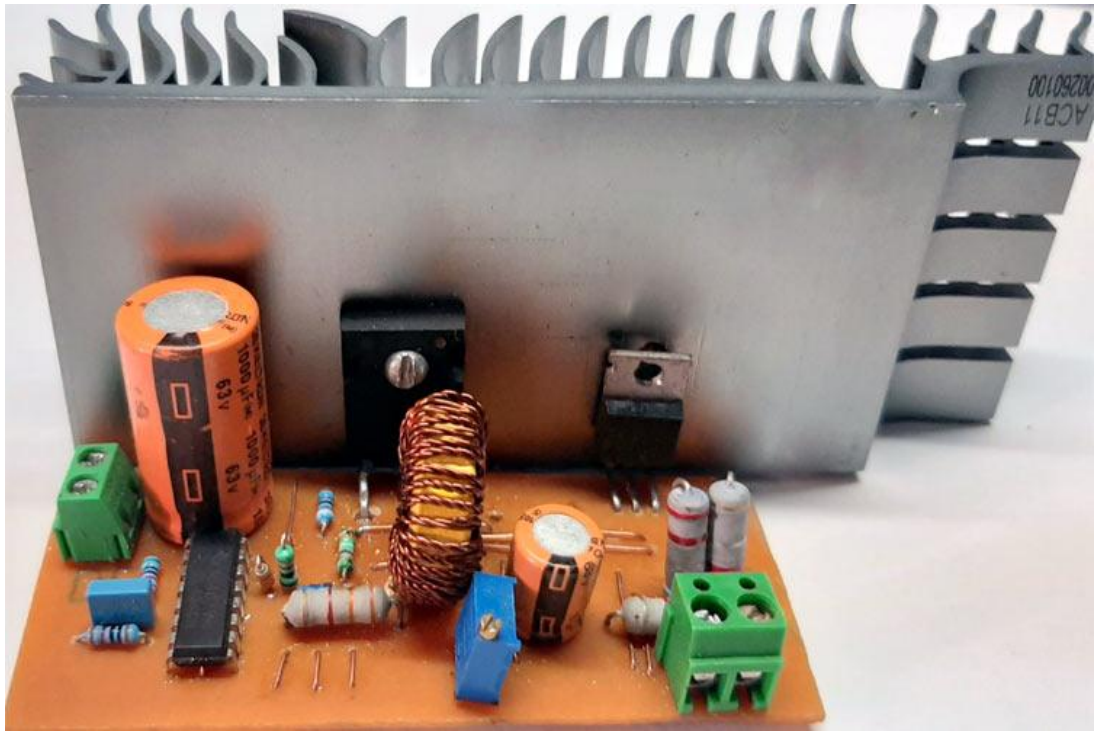
k1, k2,k3 su konstruktivni parametri i dobijaju se iz kataloških podataka ferita

GUBICI u ESR kondenzatora



$$P_{ESR} = \tilde{I}_C^{\,2} ESR$$

$$\tilde{I}_C = \frac{\Delta i_L}{2\sqrt{3}}$$



HVALA NA PAŽNJI!!!

PITANJA??

Beograd, MAJ 2021
Dr Željko Despotović, dipl.el.inž