

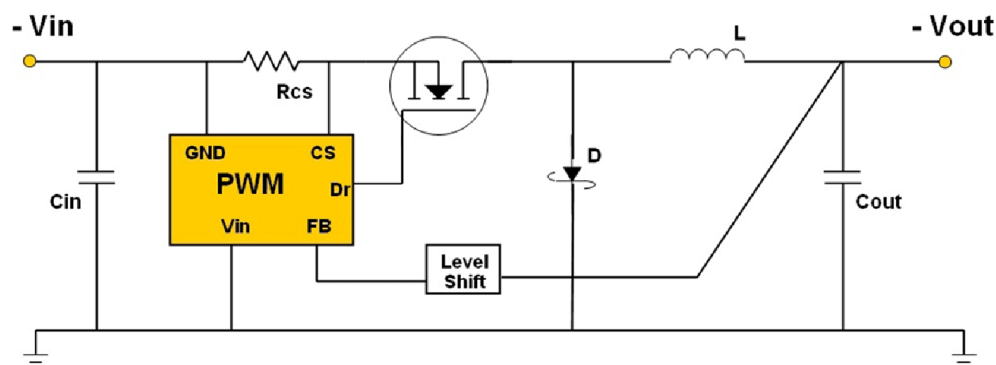
VISOKA ŠKOLA ELEKTROTEHNIKE I RAČUNARSTVA STRUKOVNIH STUDIJA-VIŠER,
BEOGRAD

STUDIJSKI PROGRAMI: MASTER STUDIJE-ELEKTROTEHNIČKO INŽENJERSTVO

PREDMET: PROJEKTOVANJE ELEKTROENERGETSKIH PRETVARAČA



DIMENZIONISANJE DC-DC PRETVARAČA SPUŠTAČA NAPONA (Step-Down Pretvarač)



Predmetni profesor: Dr Željko Despotović, dipl.el.inž.

OSNOVNA KONFIGURACIJA TOPOLOGIJE

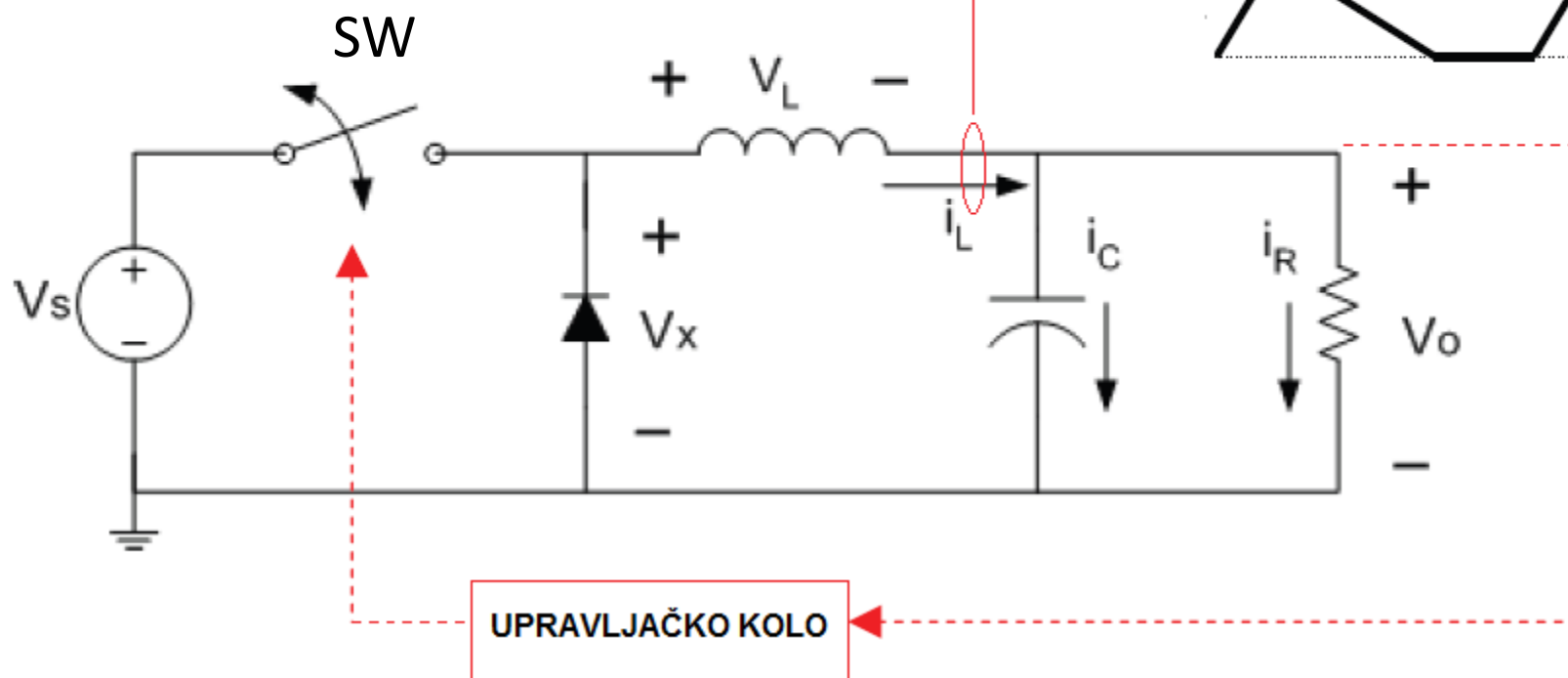
Continuous Conduction Mode (CCM)

KONTINUALNI
REŽIM RADA CCM



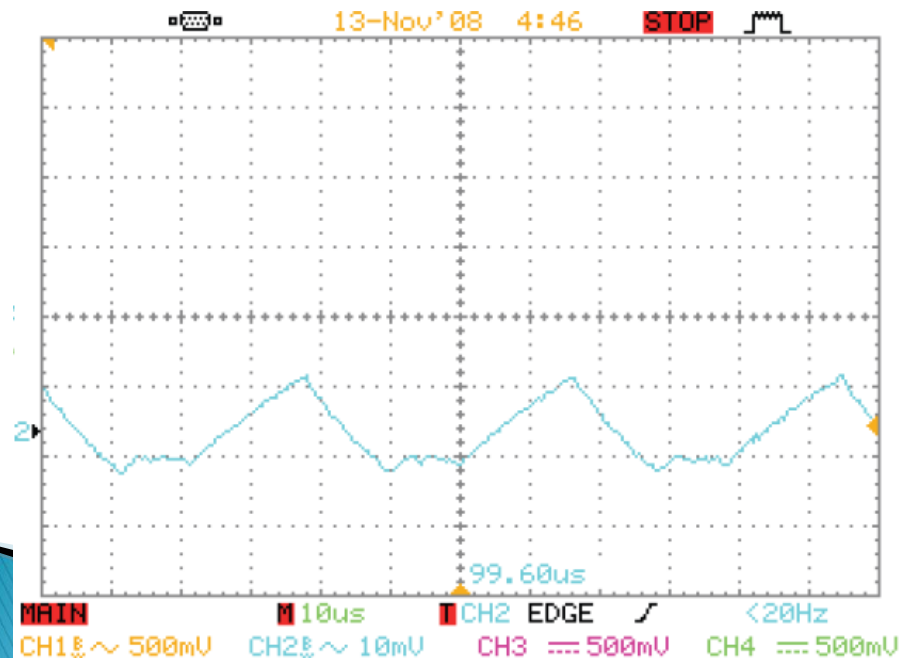
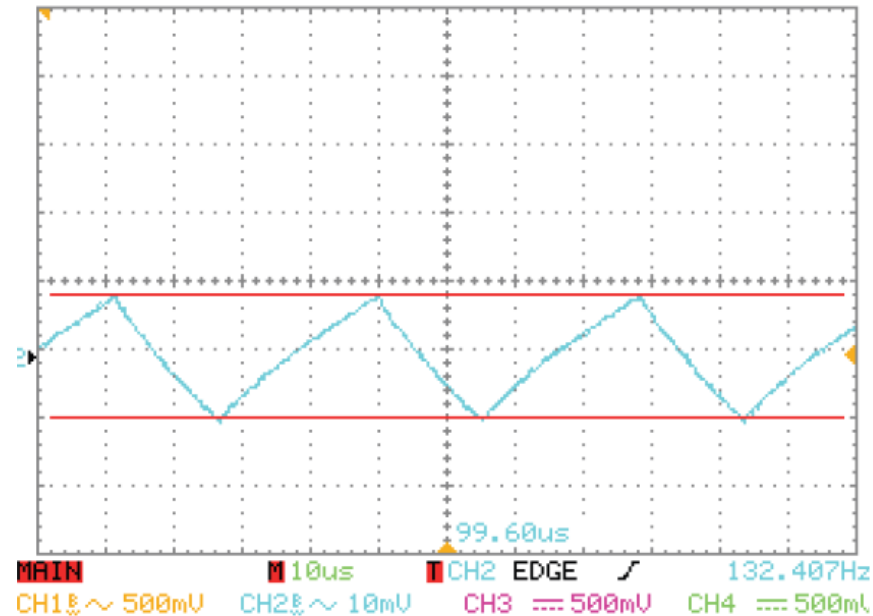
Discontinuous Conduction Mode (DCM)

DISKONTINUALNI
REŽIM RADA DCM



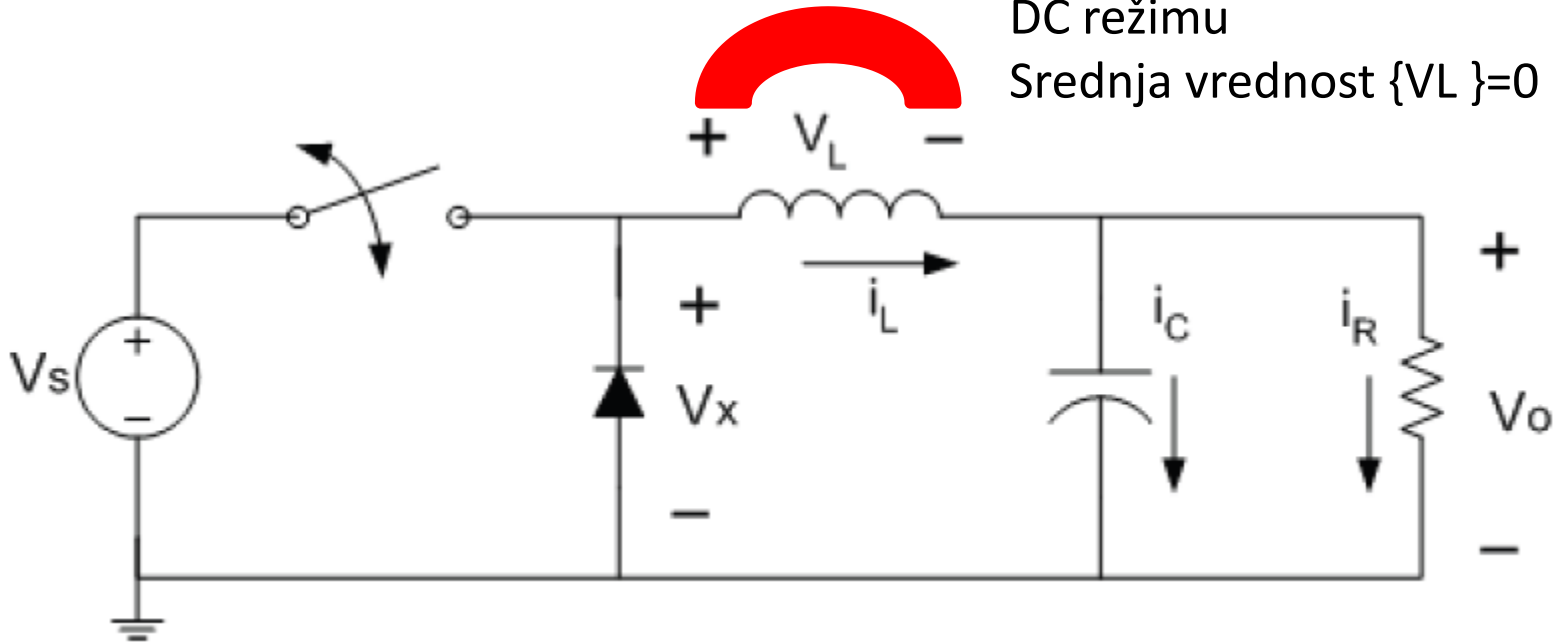
KAKO TO IZGLEDA U STVARNOSTI?

**CCM režim
ili KONTINUALNI**



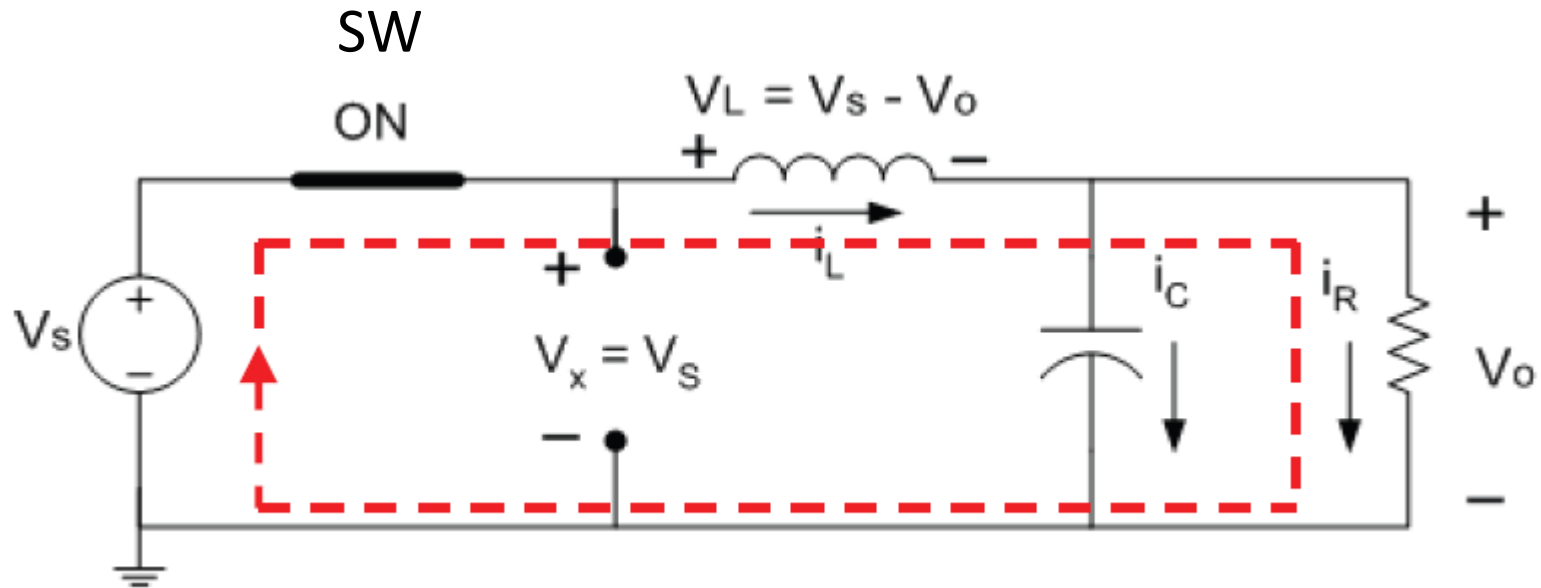
**DCM režim
ili DISKONTINUALNI**

Induktivnost je KRATAK SPOJ u
DC režimu
Srednja vrednost $\{V_L\} = 0$



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

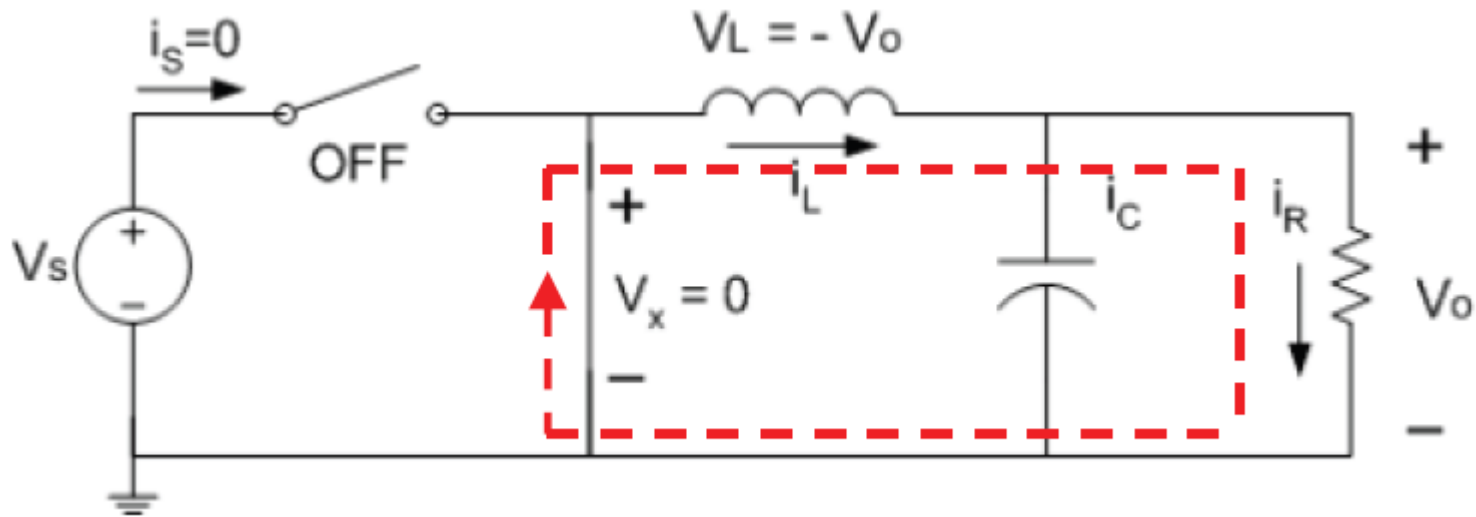
Prekidač SW zatvoren (režim u intervalu ton)



$$v_{Lon} = V_s - V_o$$

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

Prekidač SW otvoren (režim u intervalu toff)



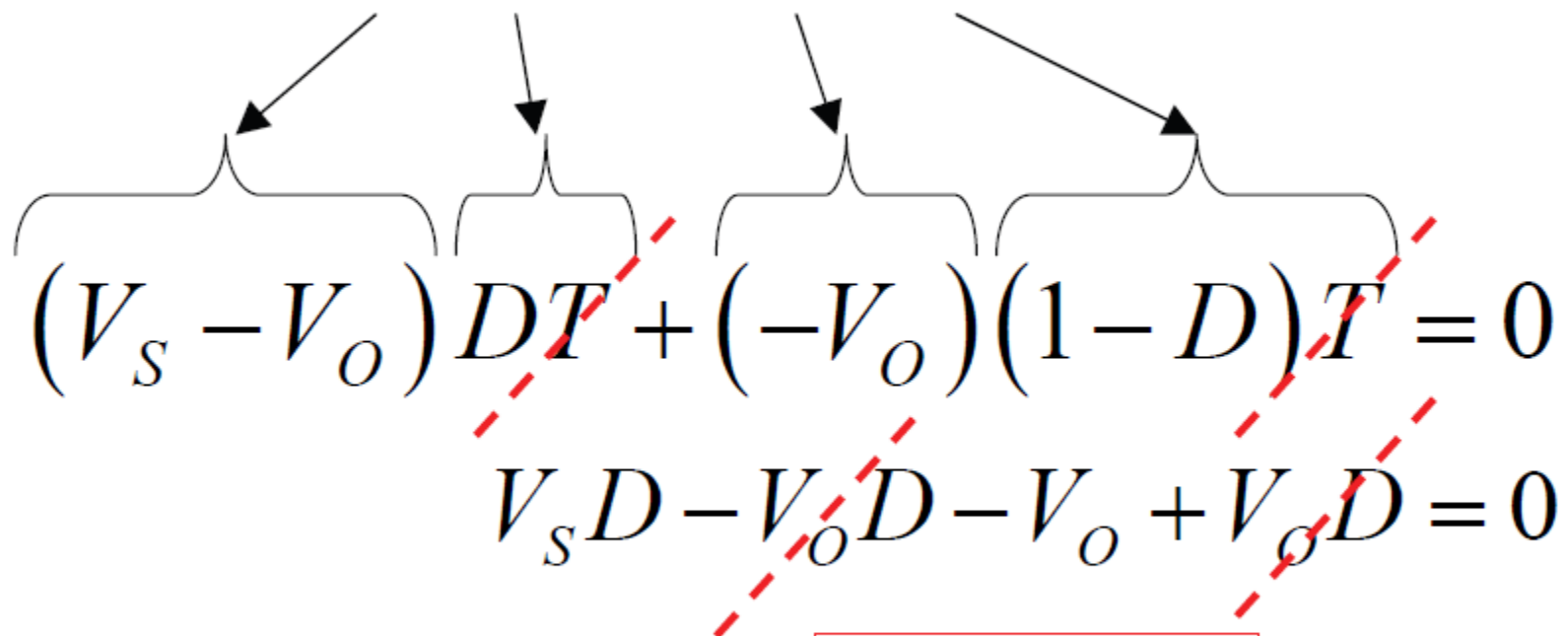
$$v_{Loff} = -V_o$$

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

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

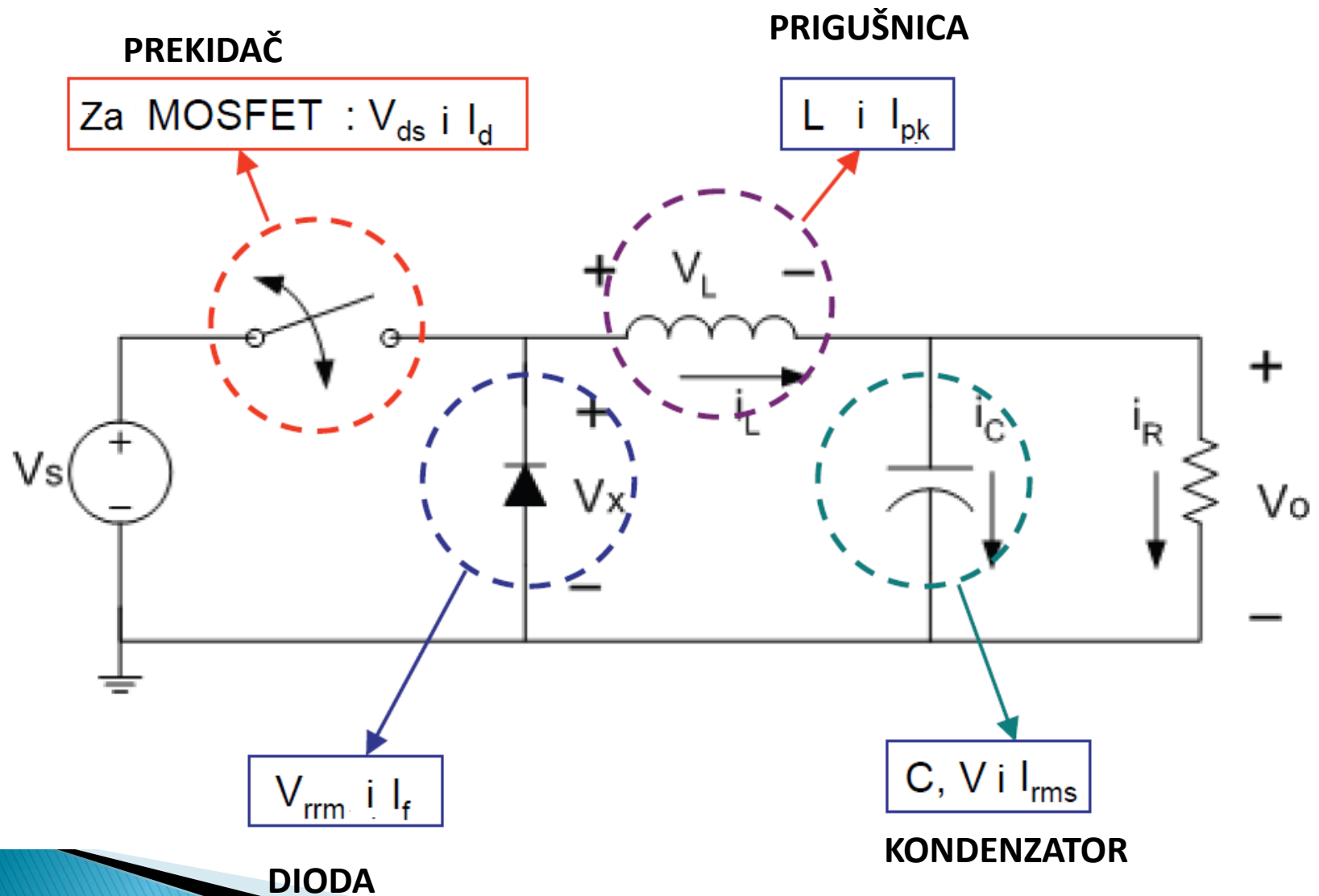
Prenosna funkcija pretvarača u ustaljenom režimu u modu CCM

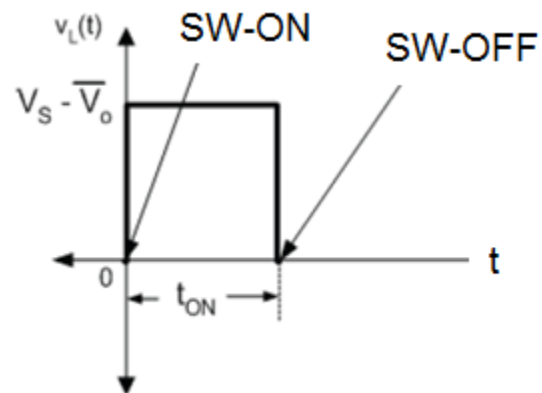
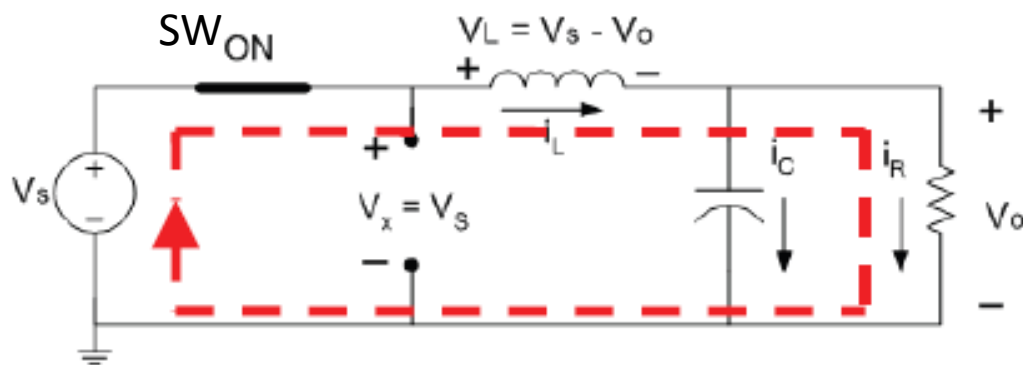
$$v_{Lon} t_{on} + v_{Loff} t_{off} = 0$$


$$(V_s - V_o) DT + (-V_o)(1 - D)T = 0$$
$$V_s D - V_o D - V_o + V_o D = 0$$

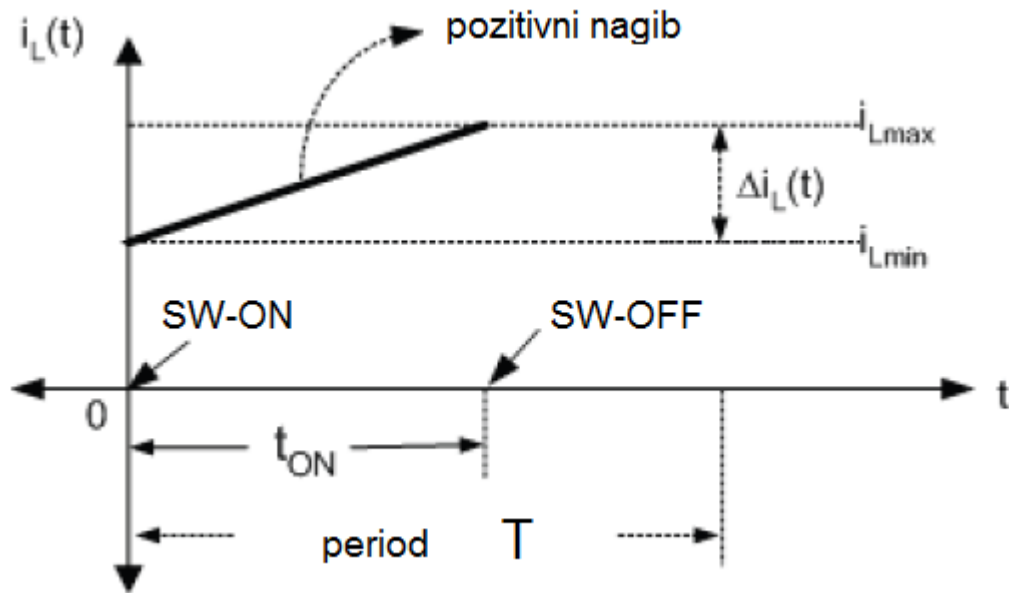
$$V_o = DV_s$$

DIMENZIONISANJE PRETVARAČA (Šta se ustvari dimenzioniše?)



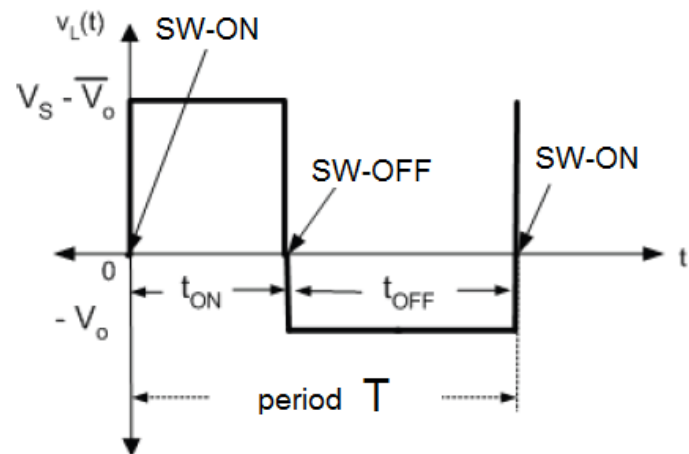
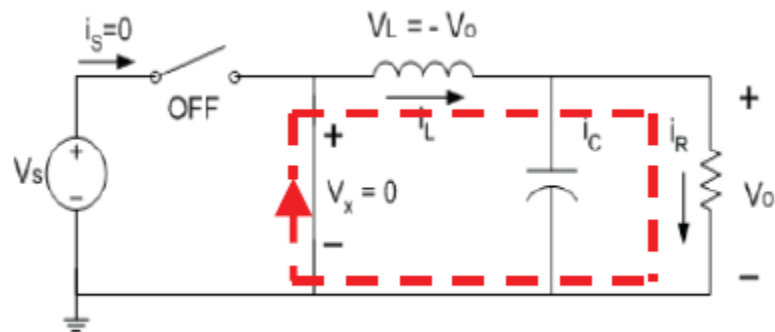


$$v_L = V_S - V_O = L \frac{di_L}{dt} \quad \longrightarrow \quad \frac{di_L}{dt} = \frac{V_S - V_O}{L} = \oplus$$

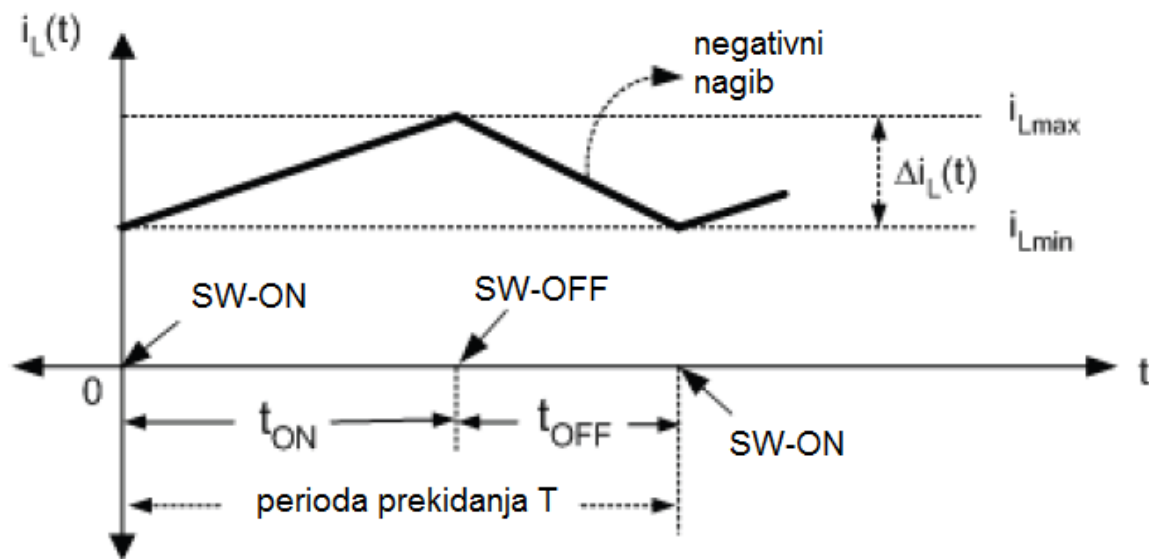


$$\Delta i_{Lon} = \frac{V_S - V_O}{L} \Delta t_{on}$$

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

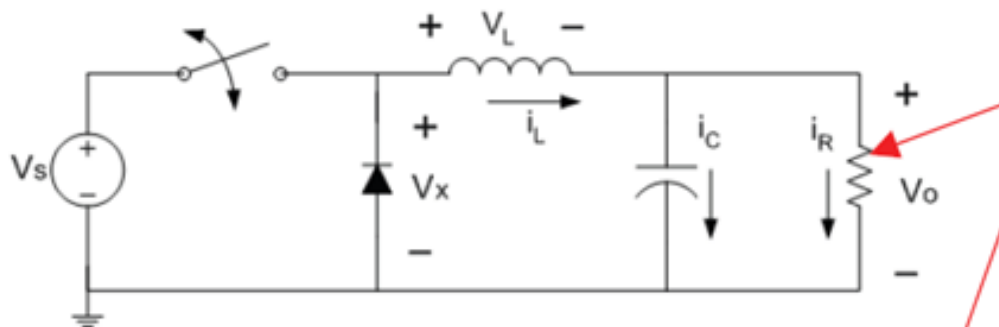


$$v_L = -V_o = L \frac{di_L}{dt} \quad \longrightarrow \quad \frac{di_L}{dt} = \frac{-V_o}{L} = \boxed{-}$$

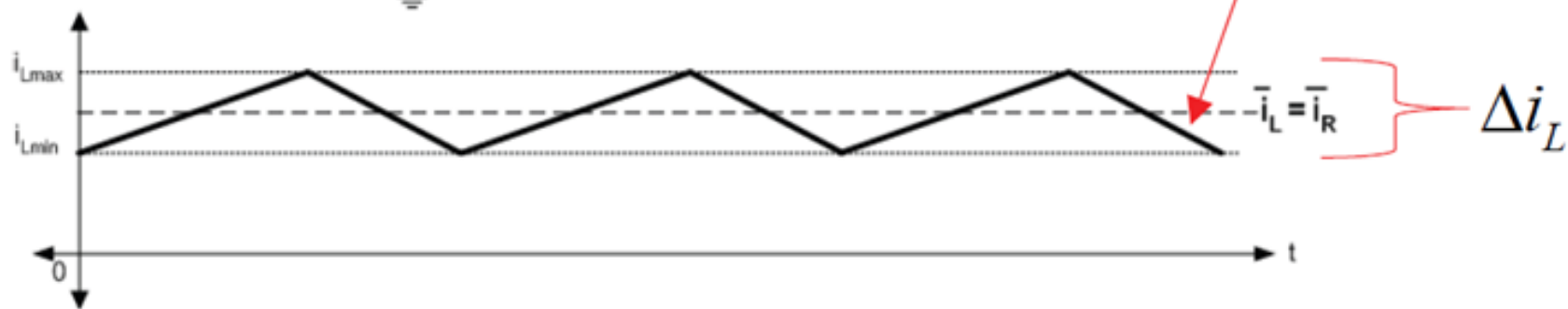


$$\Delta i_{Loff} = \frac{-V_o}{L} \Delta t_{off}$$

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



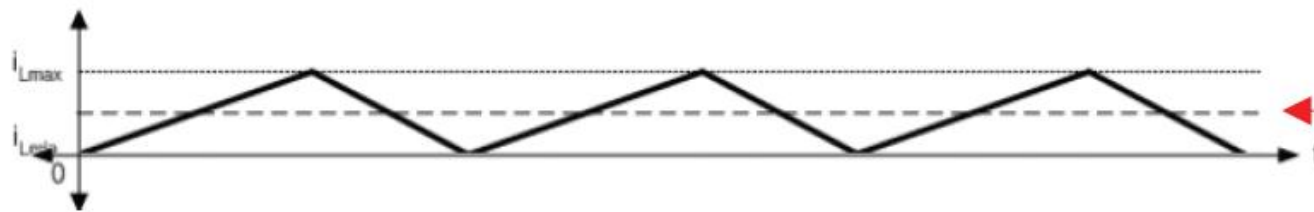
srednja vrednost
struje prigušnice je
jednaka srednjoj
vrednosti
izlazne struje V_o/R



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

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

DIMENZIONISANJE PRIGUŠNICE



Minimalna struja
opterećenja
u CCM režimu

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

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

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



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

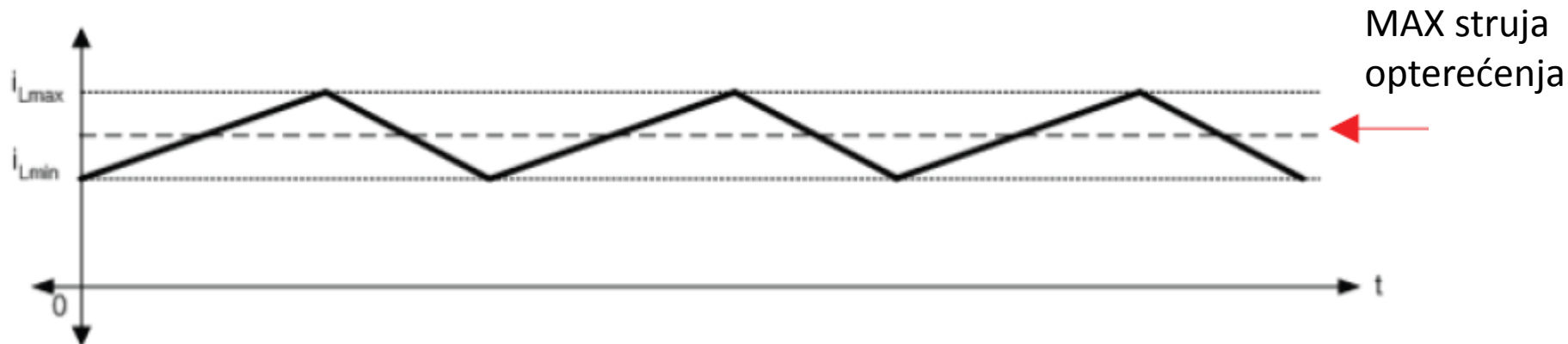
$$L_C = \frac{(1 - D_{\text{max}}) R_{\text{max}}}{2f}$$

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

Pri MIN ulaznom
naponu

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

ODREĐIVANJE MAX STRUJE PRIGUŠNICE

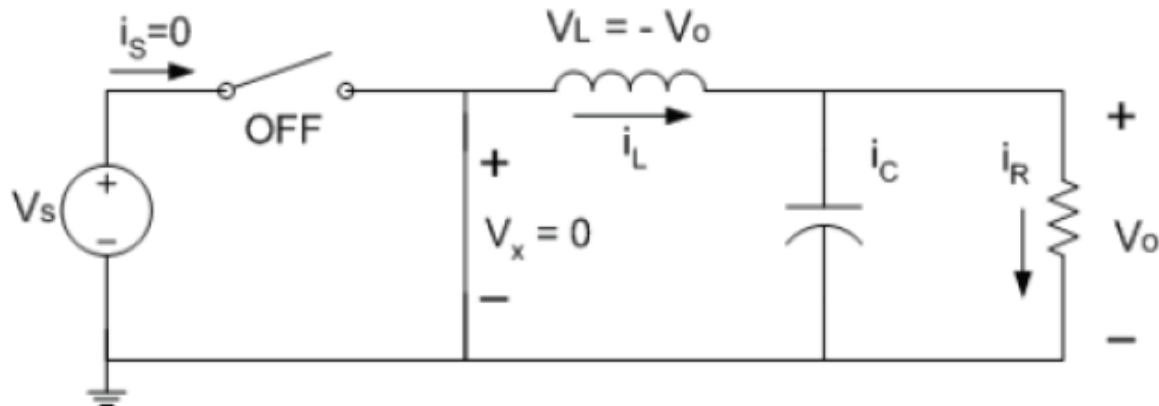


$$I_{Lmax} = \overline{I_L} + \frac{|\Delta i_L|}{2} = V_0 \left[\frac{1}{R_{min}} + \frac{(1 - D_{min})}{2Lf} \right]$$

Pri MAX
ulaznom
naponu

$$L > 1.05 \cdot L_C$$

DIMENZIONISANJE PREKIDAČA -SW



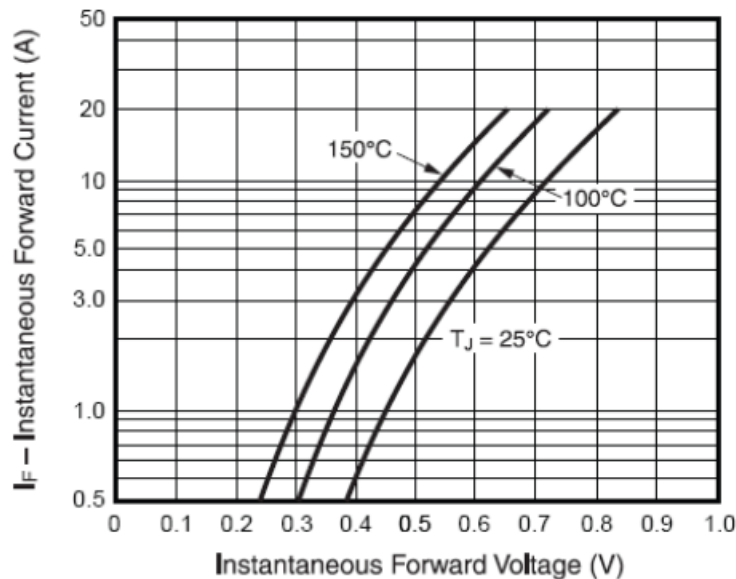
U ISKLJUČENOM STANJU
PREKIDAČ (SW)
TRPI NAJVEĆI NAPON

AKO JE DIODA IDEALNA:

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

AKO DIODA NIJE IDEALNA:

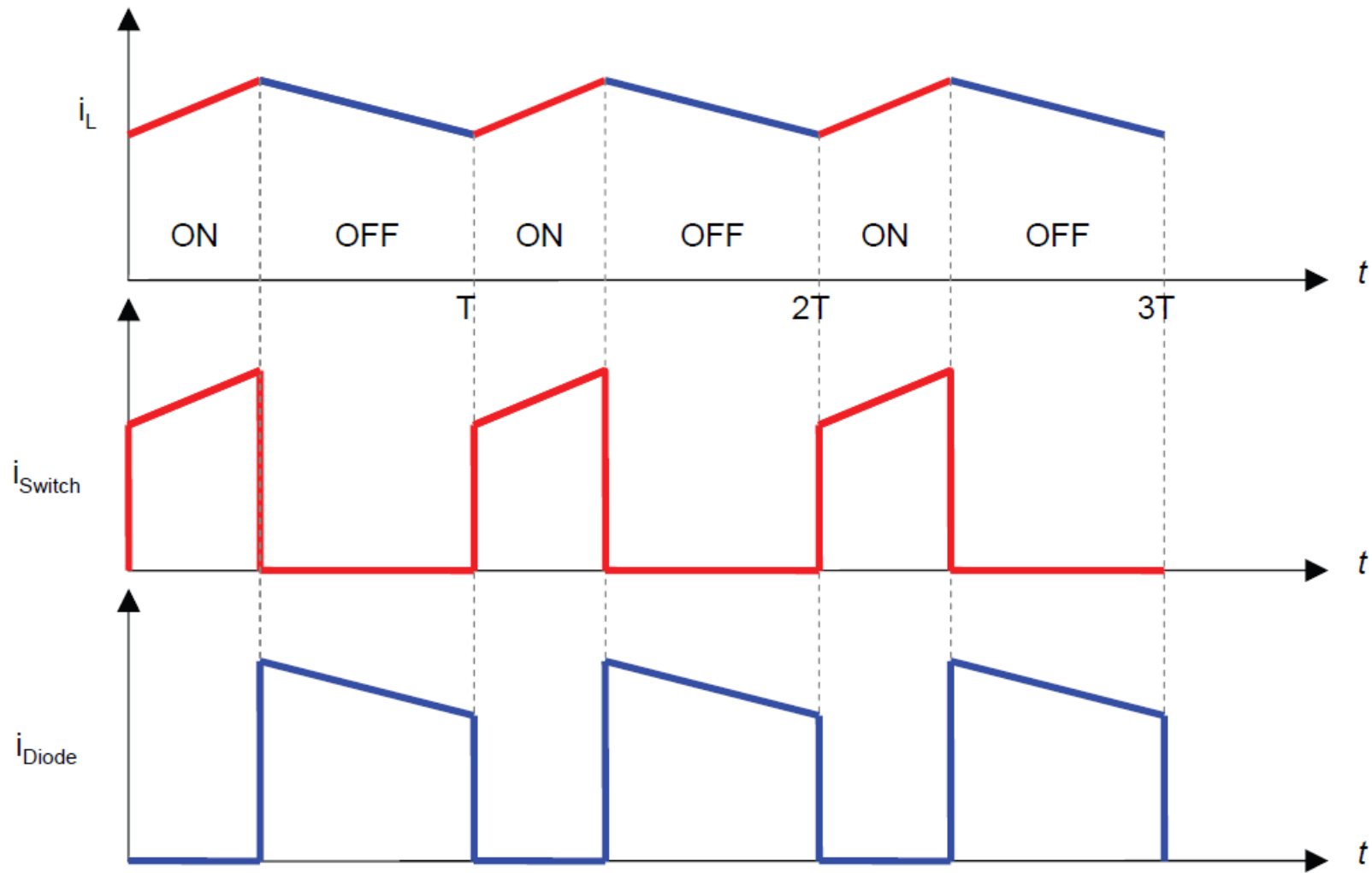
$$V_{\text{switch-max}} = V_{\text{inmax}} + V_F$$

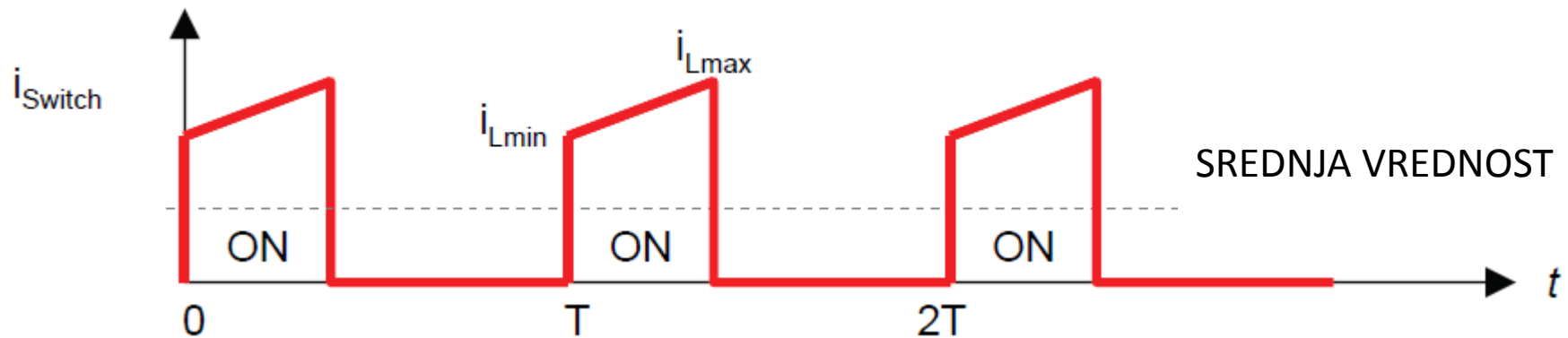


KARAKTERISTIKA
TIPIČNE DIODE

ZA NAPON PREKIDAČA V_{ds} SE USVAJA 20%
VEĆI NAPON OD V_{sw-max} !!!!

STRUJA PREKIDAČA ?





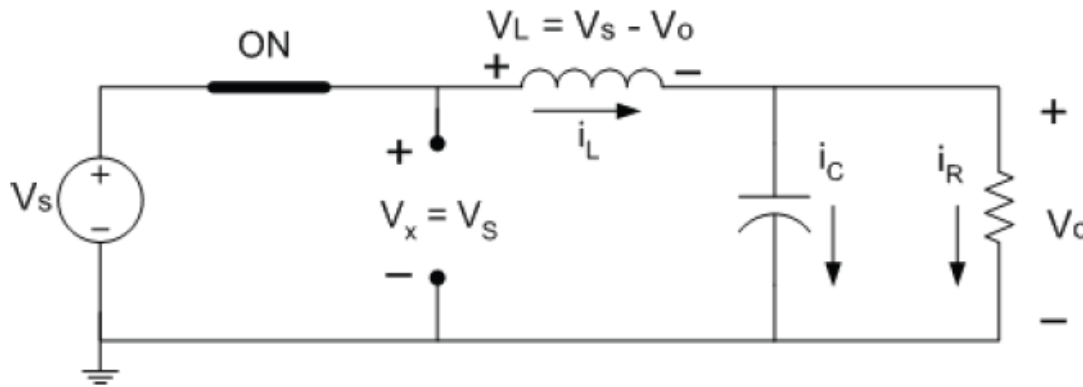
$$\overline{I_{\text{Switch}}} = \frac{(i_{L\min} + i_{L\max}) \cdot t_{\text{on}}}{2 \cdot T}$$

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

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

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

DIMENZIONISANJE DIODE (obično je to Šotki dioda)



Kada je SW uključen
dioda trpi INVERZNI NAPON !!

KADA JE PREKIDAČ IDEALAN:

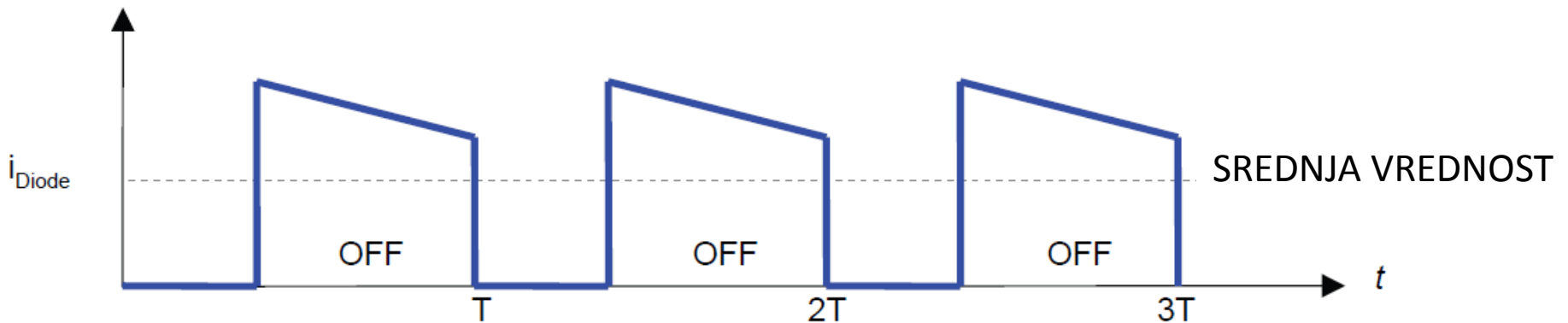
$$V_{RRM} = V_{inmax}$$

KADA PREKIDAČ NIJE IDEALAN:

$$V_{RRM} = V_{inmax} + V_{SW}$$

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

STRUJA DIODE ?



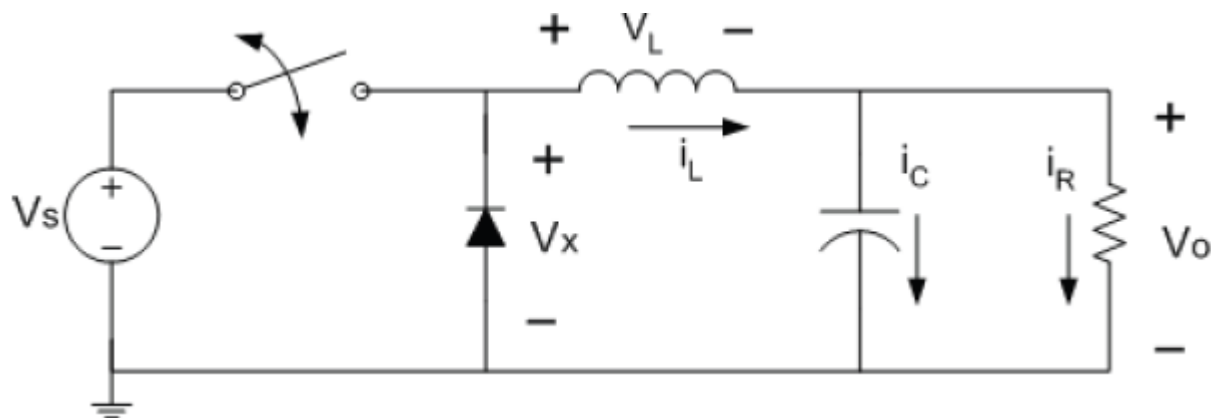
$$\overline{I_F} = \frac{(i_{L\min} + i_{L\max}) \cdot t_{\text{off}}}{2 \cdot T}$$

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

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

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

DIMENZIONISANJE KONDENZATORA



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

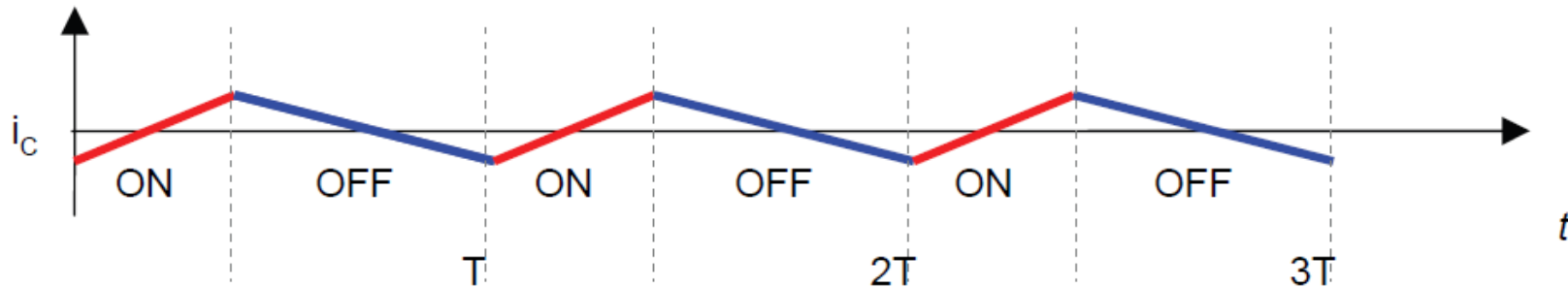
ESR (Equivalent Series Resistance)

-utiče na dodatno povećanje ripla napona ΔV_o

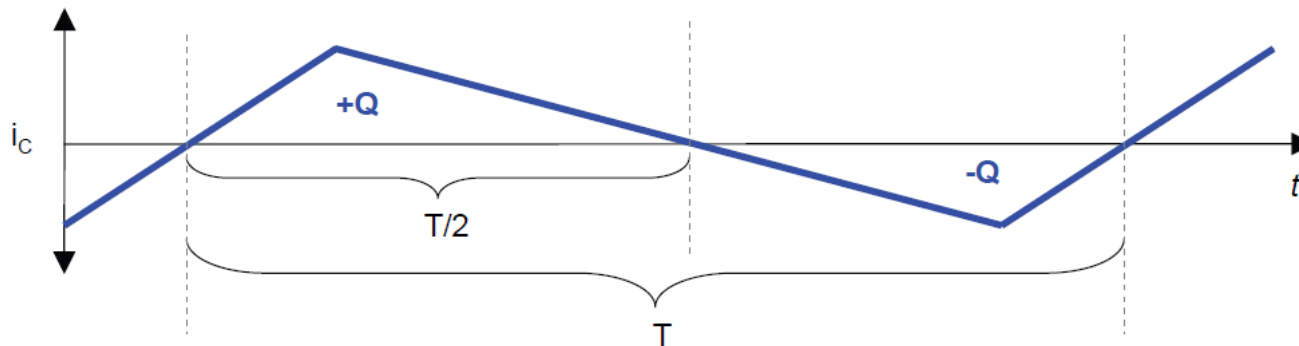
-dodatno povećanje ripla napona: $ESR * \Delta I_L$

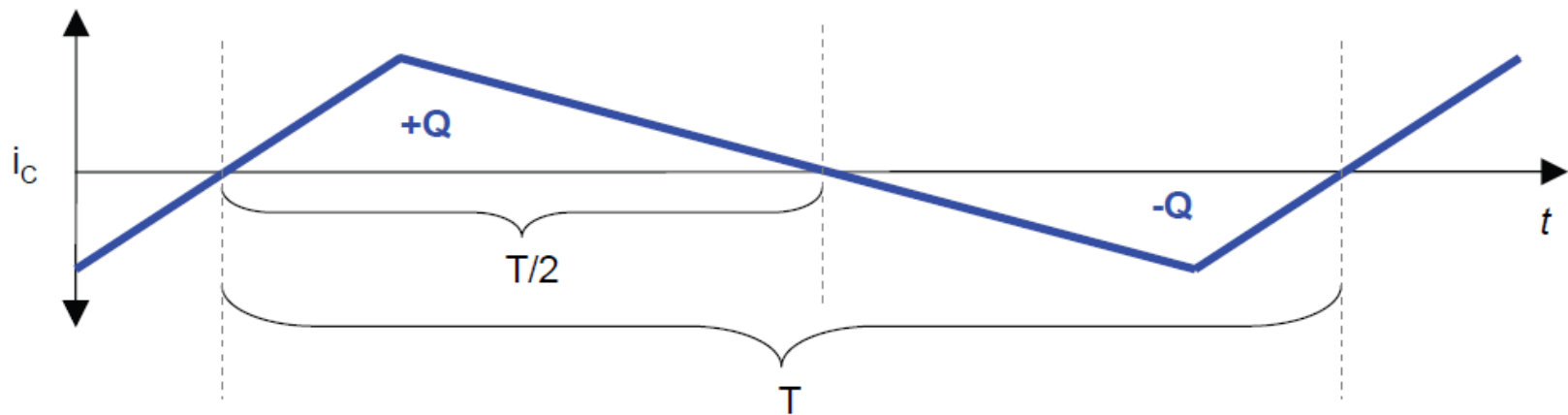
Težnja je da ESR bude što manje , kao i talasnost struje !!!!

KAKO PRORAČUNATI MIN KAPACITIVNOST?



Kroz kondenzator protiče AC(naizmenična) komponenta struje prigušnice





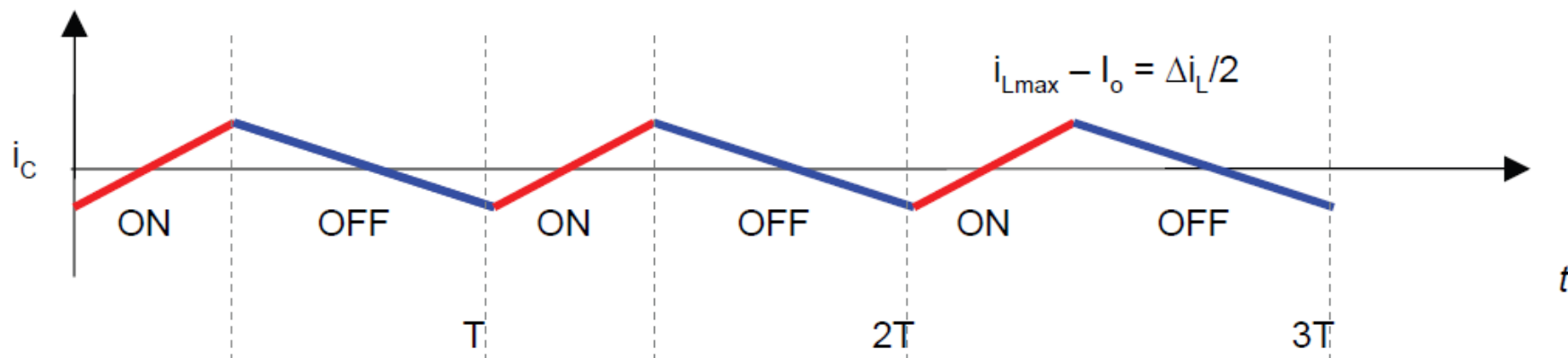
$$q = P_{\Delta} = \frac{1}{2} \left(\frac{T}{2} \right) \left(\frac{\Delta i_L}{2} \right) = \frac{\Delta i_L}{8f} = \frac{\frac{V_o}{L} (1-D) T}{8f} = \frac{(1-D) V_o}{8Lf^2}$$

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

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

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

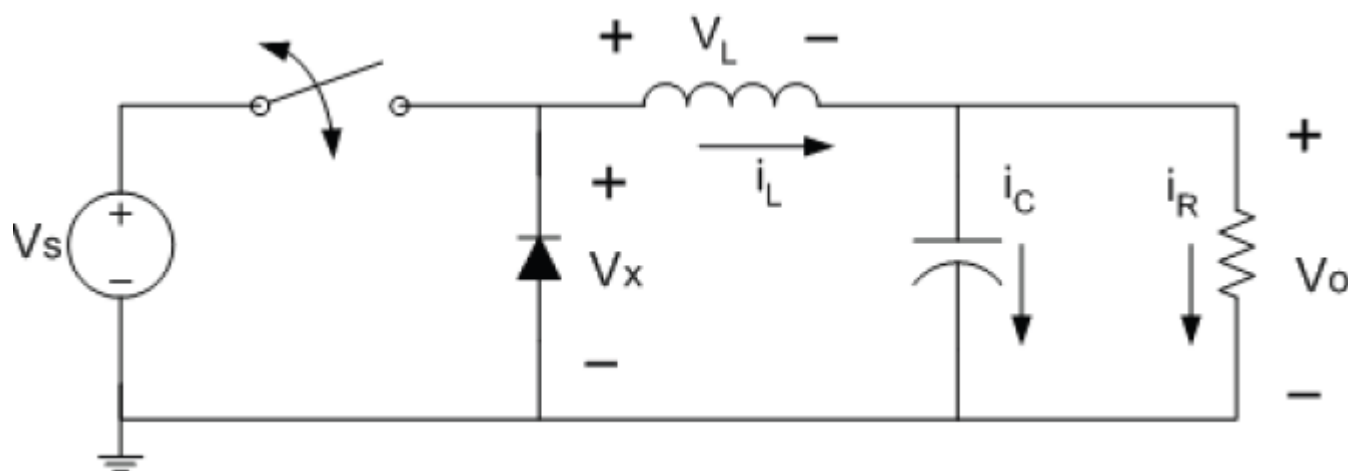
EFEKTIVNA VREDOST STRUJE KONDENZATORA?



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

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

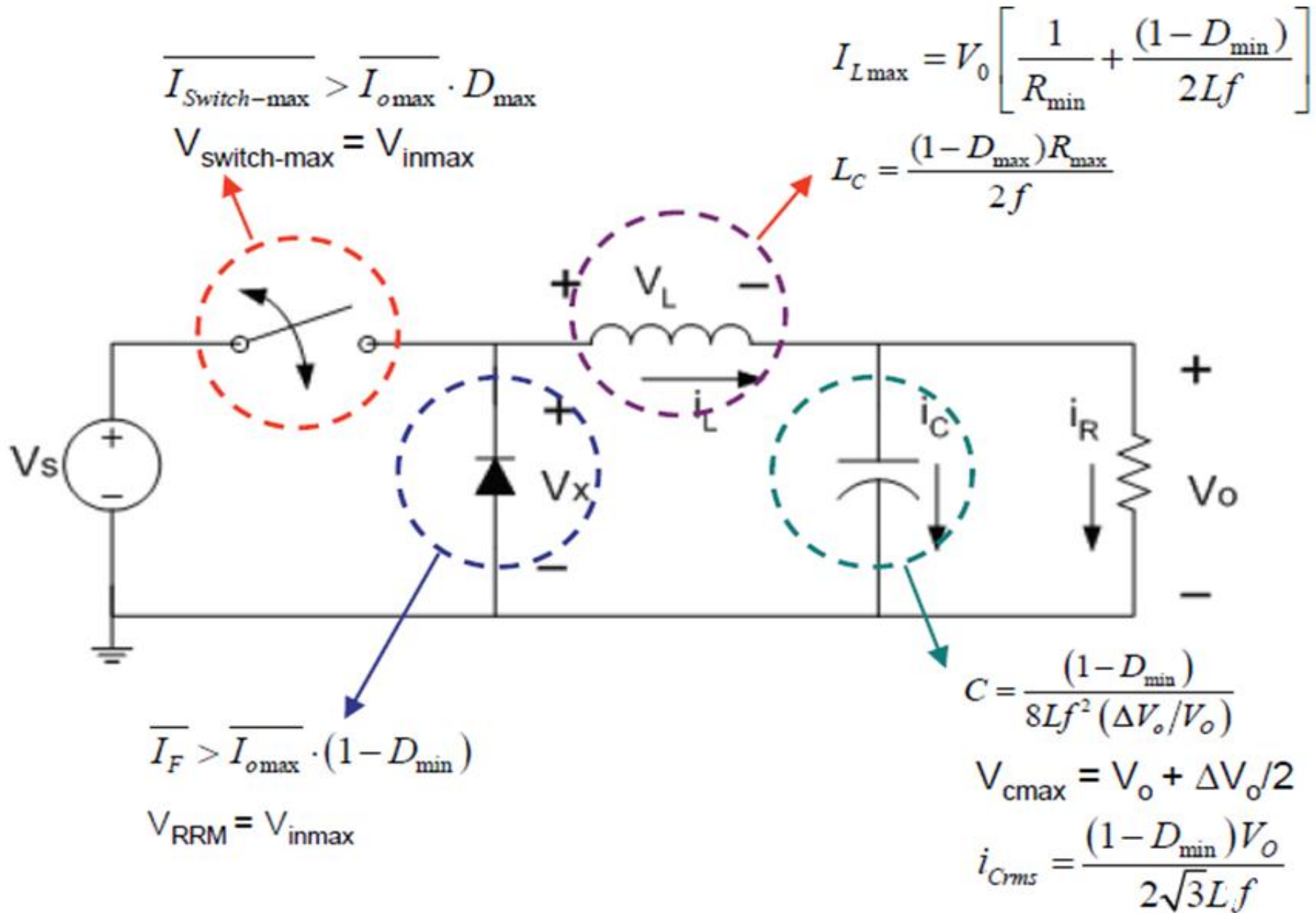
MAX NAPON KONDENZATORA ?



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

Kada je $D=1$ (prekidač je dovoljno dugo uključen) $V_c=V_{in}$

SUMARNO:



PRIMER 1 ZA VEŽBU:

Spuštač napona 12V/2.5V, 1A

$f=50\text{kHz}$

talasnost struje $< 10\%$

talasnost napona $< 1\%$

Dimenzionisati komponente pretvarača
zanemarujući gubitke?

KAKO UZETI U OBZIR GUBITKE U PRETVARAČU?

Koji sve postoje gubici??

MOSFET:

- Statički gubici u MOSFET prekidaču
- Prekidački dinamički gubici u MOSFET prekidaču
- Gubici u pobudnom kolu MOSFET prekidača

DIODA:

- Statički gubici
- Prekidački gubici

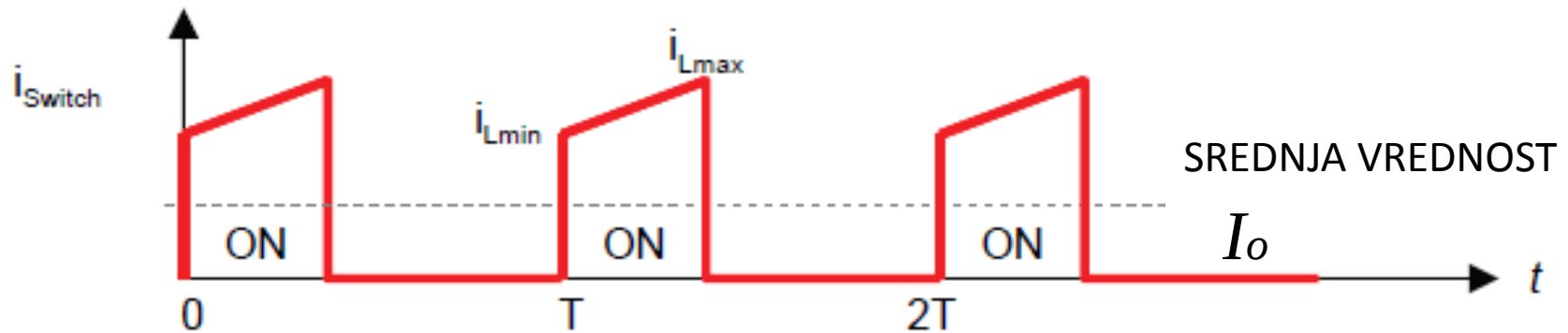
PRIGUŠNICA:

- gubici u bakru
- gubici u gvožđu

KONDENZATOR:

- gubici u ekvivalentnoj serijskoj otpornosti (ESR)

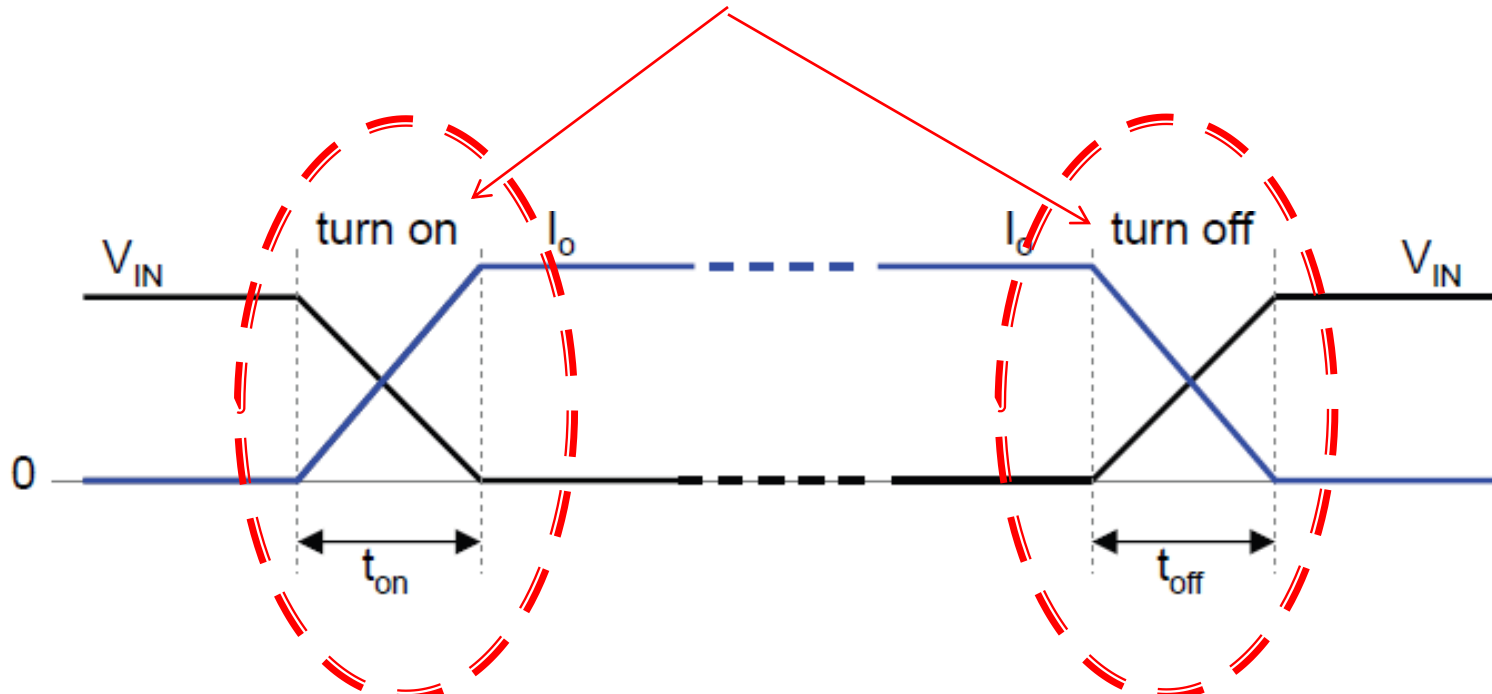
STATIČKI GUBICI MOSFET PREKIDAČA



$$P_{\text{static}} = I_{\text{switch-rms}}^2 \cdot R_{\text{DSon}}$$

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

DINAMIČKI GUBICI MOSFET PREKIDAČA



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

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

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

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

PREKIDAČKI GUBICI U POBUDNOM KOLU MOSFET PREKIDAČA

KADA JE MOSFET ISKLJUČEN, PUNI SE KAPACITIVNOST C_{oss} :

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

PREKIDAČKI GUBICI U KOLU GEJTA:

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

STATIČKI GUBICI DIODE U STANJU PROVOĐENJA

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

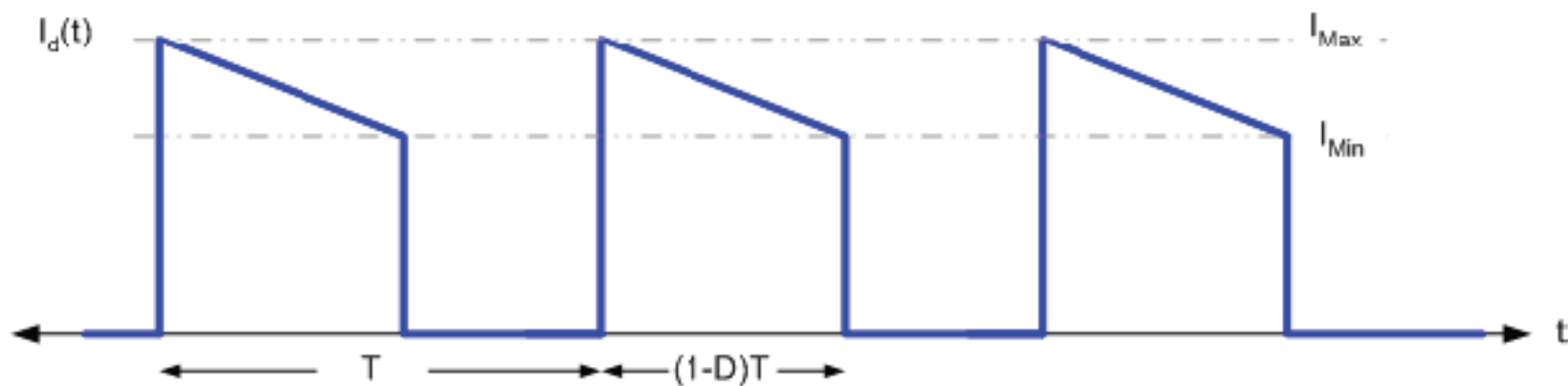
* PAD NAPONA U
STANJU VOĐENJA

SREDNJA VREDNOST
STRUJE DIODE

DINAMIČKA
OTPORNOST
DIODE *

EFEKTIVNA VREDNOST
STRUJE DIODE

* KATALOG PROIZVOĐAČA



IZ KATALOGA
PROIZVOĐAČA

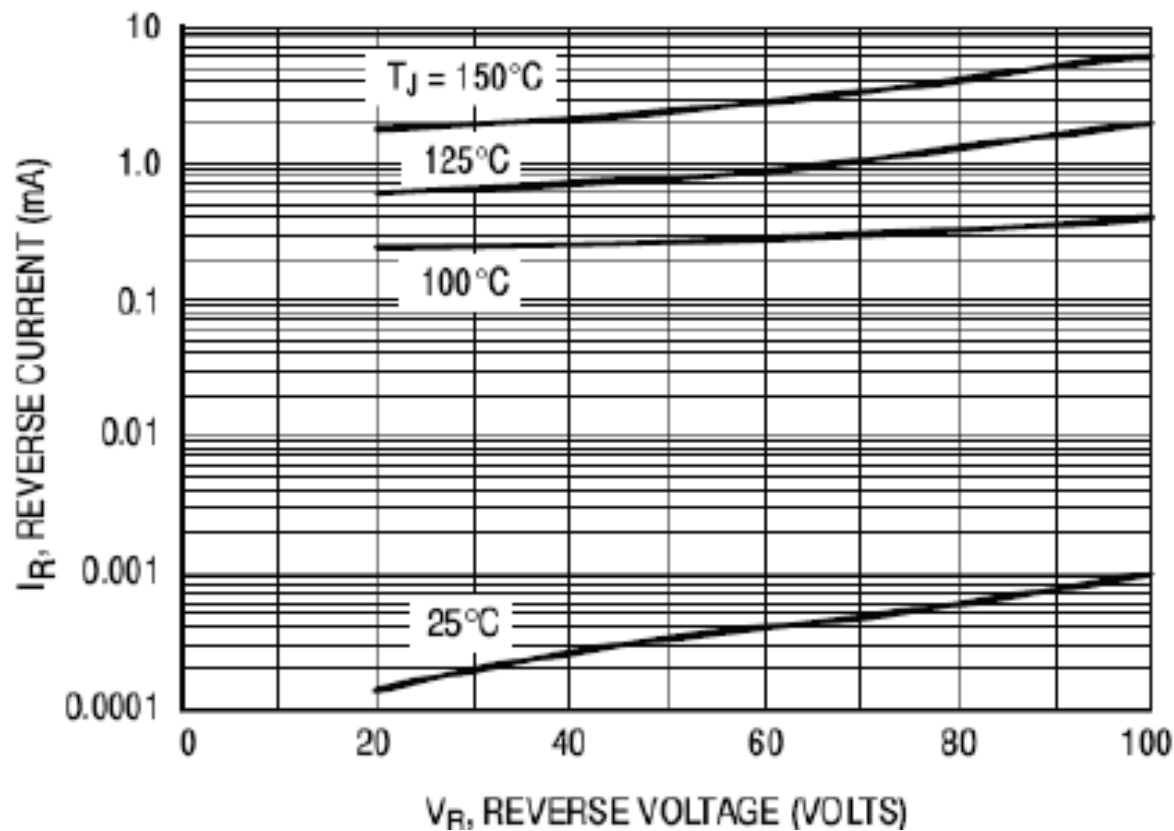
$$P_{forward} = V_f \cdot \overline{I_f} + \widetilde{I_f}^2 \cdot r_d$$

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

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

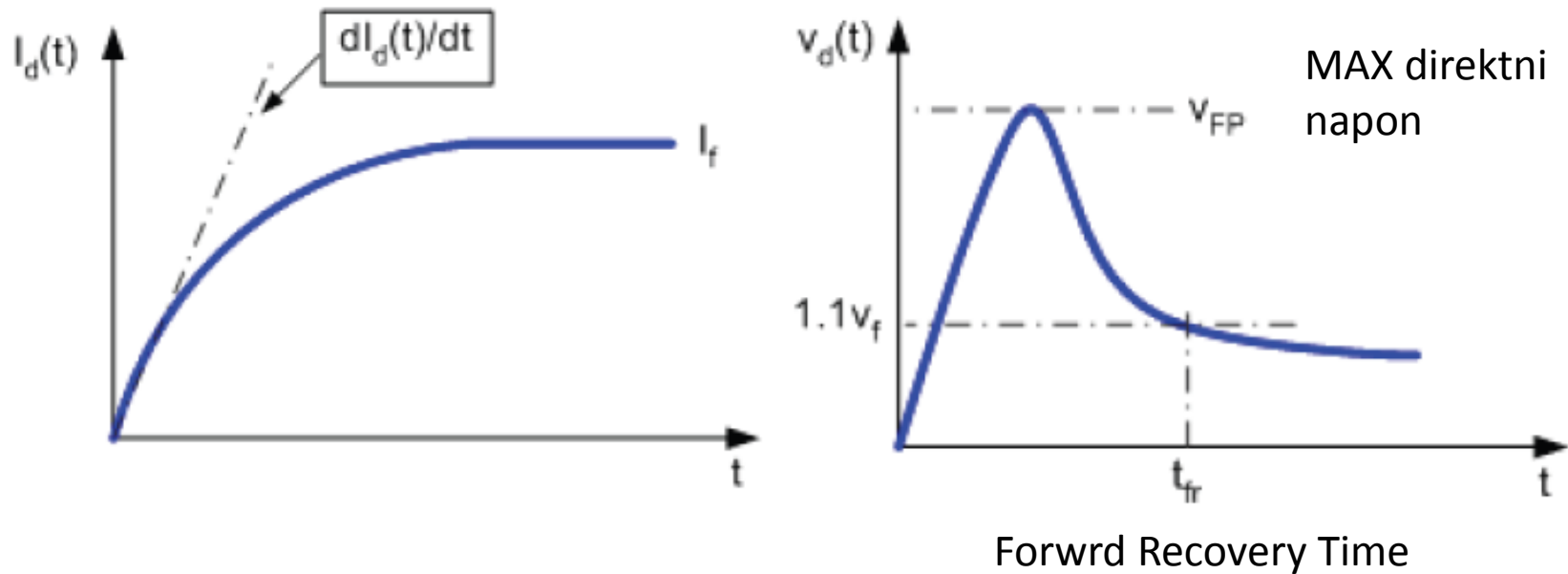
STATIČKI GUBICI DIODE U INVERZNOM REŽIMU (odnosno u STANJU NEPROVOĐENJA)

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



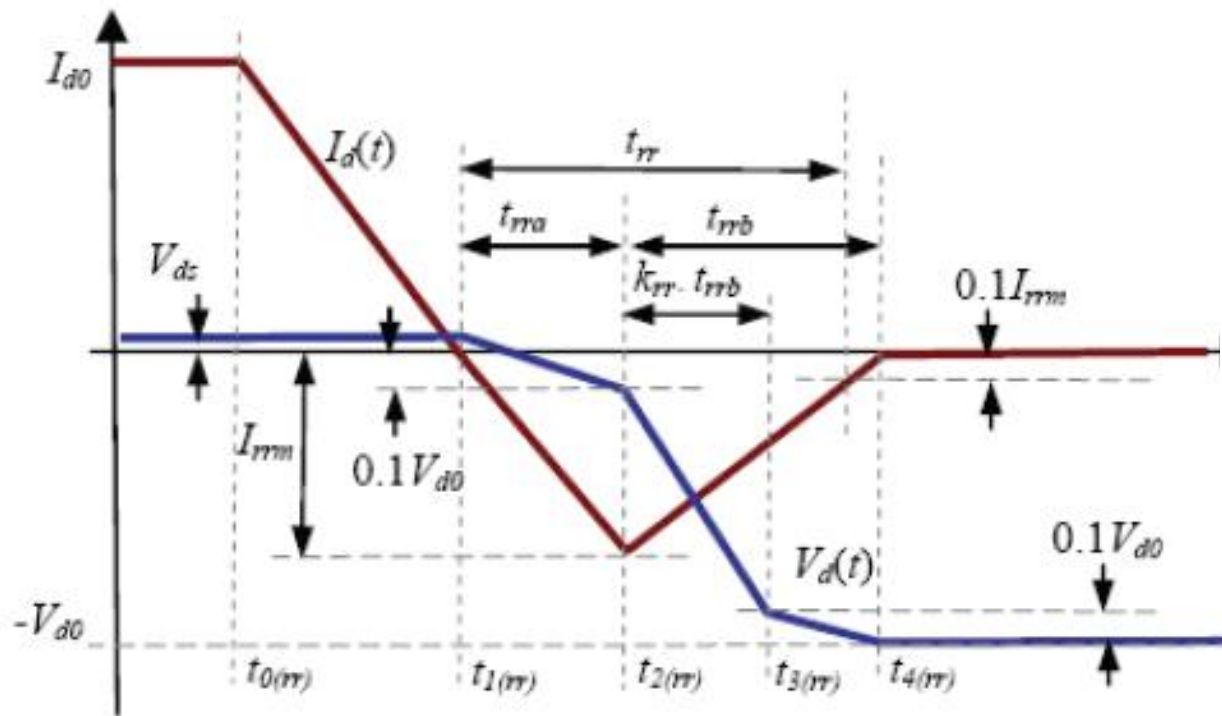
TIPIČNA KARAKTERISTIKA DIODE U INVERZNOM REŽIMU

PREKIDAČKI GUBICI DIODE PRI UKLJUČENJU



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

PREKIDAČKI GUBICI DIODE PRI ISKLJUČENJU



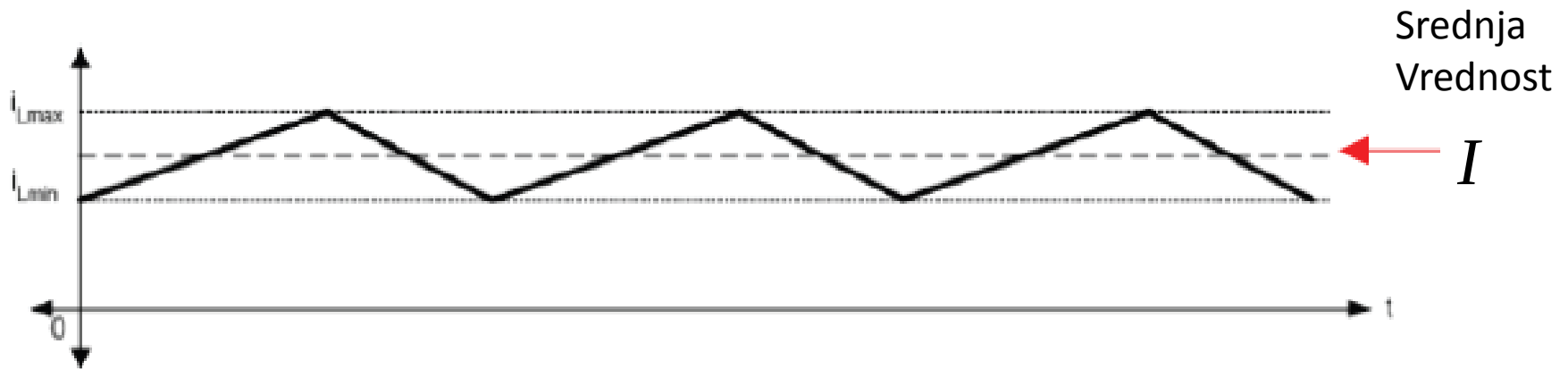
$$t_{rra} = I_{rrm} / \left(\left. \frac{dI_d}{dt} \right|_{t_{1(rr)}} \right)$$

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

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

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

GUBICI u OTPORU INDUKTIVNOSTI (gubici u bakru)



$$P_L = \tilde{I}_L^2 R_L$$

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

GUBICI u FERITNOM JEZGRU INDUKTIVNOSTI (gubici u gvožđu)

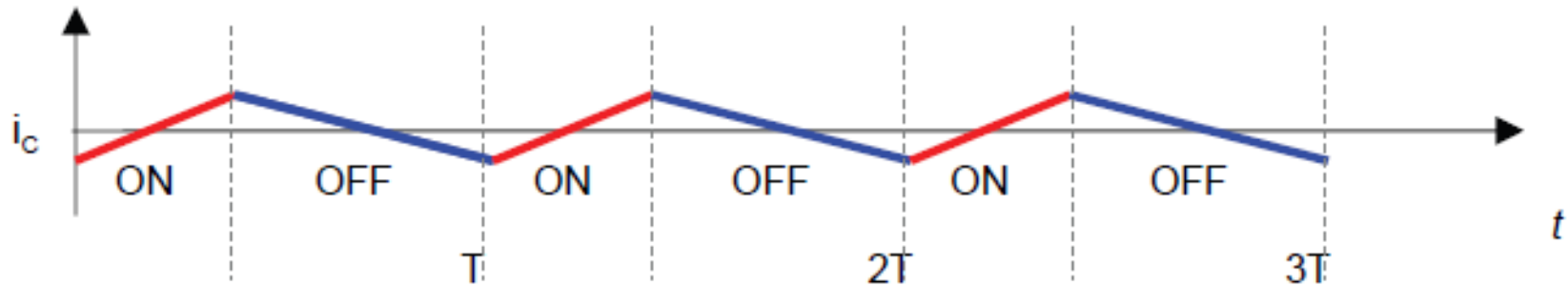
$$= k_1 \times B^{k_2} \times F^{k_3} \times V_{Fe}$$

V_{Fe} - zapremina feritnog jezgra

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

**k_1, k_2, k_3 su konstruktivni parametri i
dobijaju se iz kataloških podataka ferita**

GUBICI u ESR kondenzatora



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

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

PRIMER 2 ZA VEŽBU:

Spuštač napona 24V/12V

$P_{out}=120W$

$f=250kHz$

talasnost struje $< 10\%$

talasnost napona $< 2\%$

Dimenzionisati komponente pretvarača
uzimajući u obzir gubitke?

PRIMER 3 ZA VEŽBU:

Spuštač napona 48V/12V

$P_{out}=1200W$

$f=100kHz$

talasnost struje $< 10\%$

talasnost napona $< 2\%$

Dimenzionisati komponente pretvarača
uzimajući u obzir gubitke?



HVALA NA
PAŽNJI!!!

PITANJA??

Beograd, NOVEMBAR 2016
Dr Željko Despotović, dipl.el.inž