

VISOKA ŠKOLA ELEKTROTEHNIKE I RAČUNARSTVA STRUKOVNIH STUDIJA-VIŠER,
BEOGRAD

STUDIJSKI PROGRAM: NET, ELITE, ASUV

OSNOVNE STUDIJE 2016/2017

PREDMET: ENERGETSKA ELEKTRONIKA



NEKONTROLISANI AC/DC ENERGETSKI PRETVARAČI (DIODNI ISPRAVLJAČI)

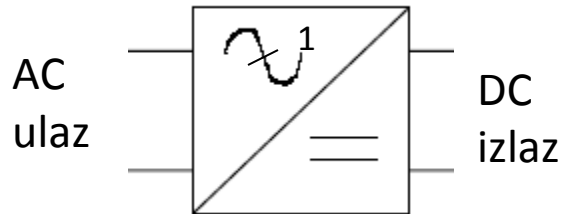


PREDMETNI PROFESOR:
Dr Željko Despotović, dipl.el.inž

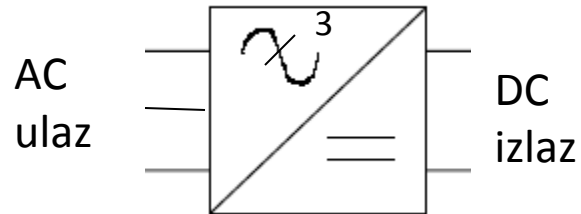
AC/DC pretvarači-ISPRAVLJAČI

AC ulaz: monofazni ili trofazni

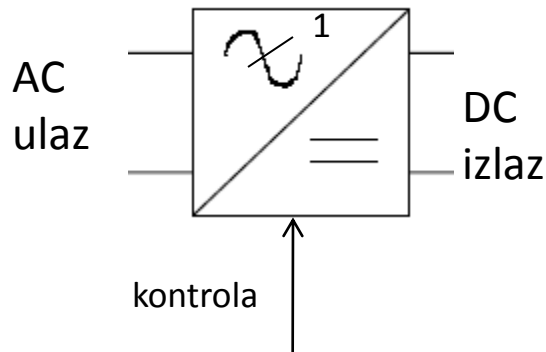
220V, 50/60Hz
3x380/220V, 50/60Hz



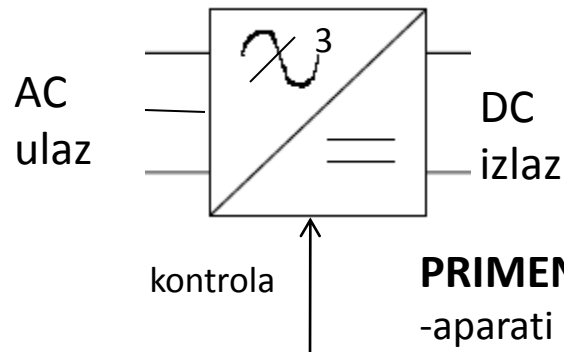
MONOFAZNI DIODNI ISPRAVLJAČI



TROFAZNI DIODNI ISPRAVLJAČI



**KONTROLISANI
TIRISTORSKI ili TRANZISTORSKI ISPRAVLJAČI
MONOFAZNI , TROFAZNI**

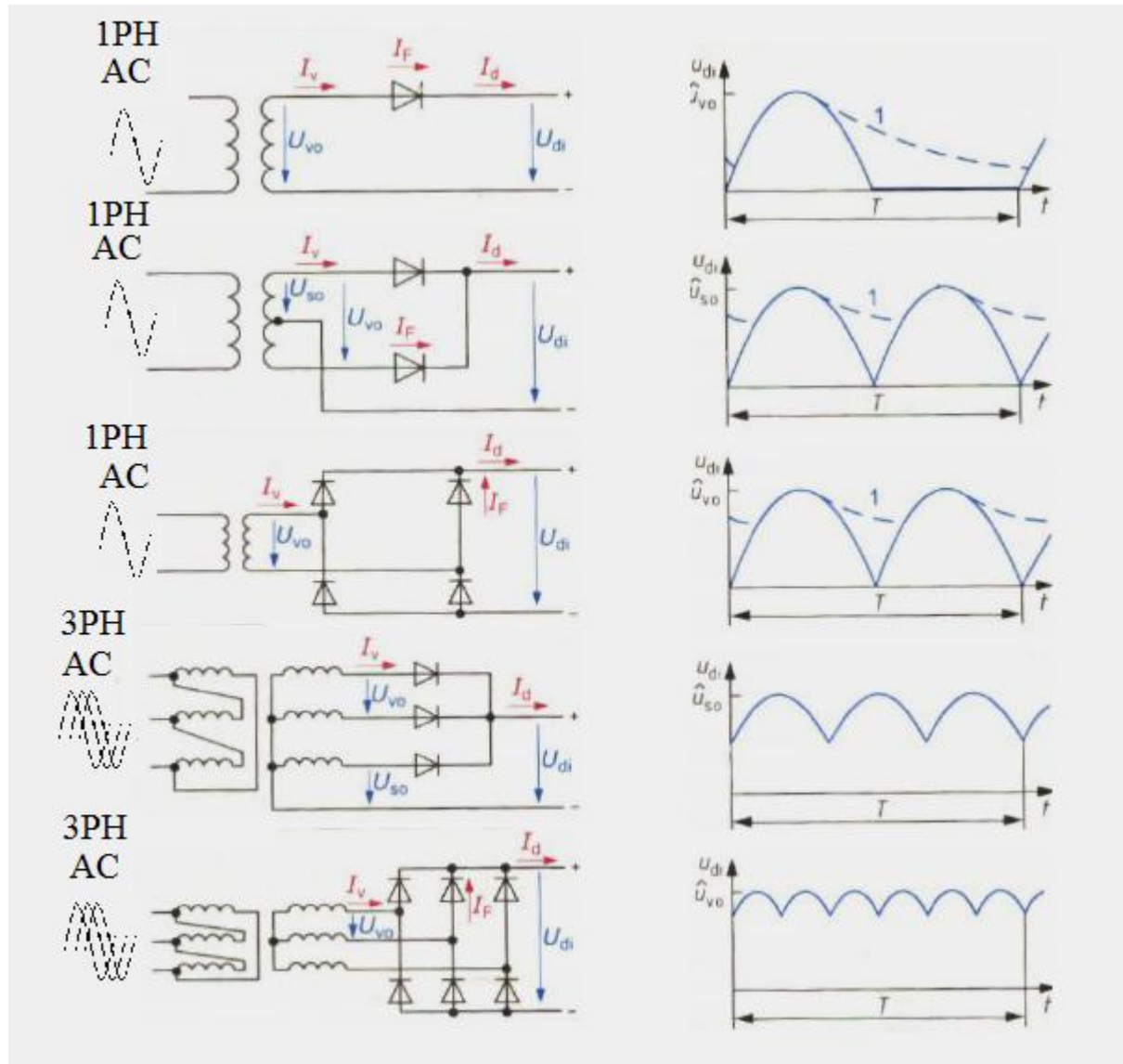


PRIMENA:

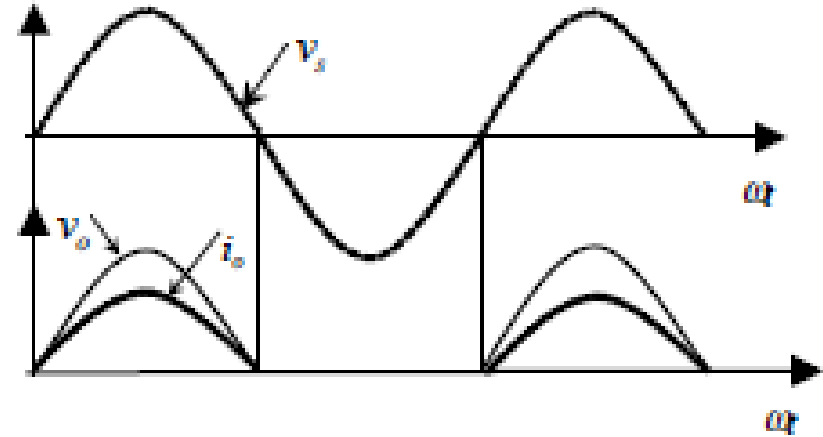
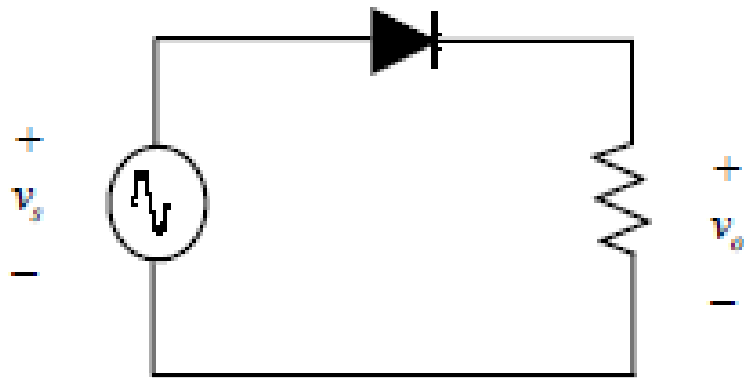
- aparati za zavarivanje
- jednosmerni motorni pogoni
- punjači baterija
- jednosmerni izvori napajanja
- visokonaponske DC aplikacije
- DC transmisije dalekovodima

TIRISTORSKI: POLUUPRAVLJIVI I PUNOUPRAVLJIVI

NEUPRAVLJIVI AC/DC PRETVARAČI DIODNI ISPRAVLJAČI



IDEALNI POLUTALSANI ISPRAVLJAČ: MONOFAZNI-OTPORNO OPTEREĆENJE



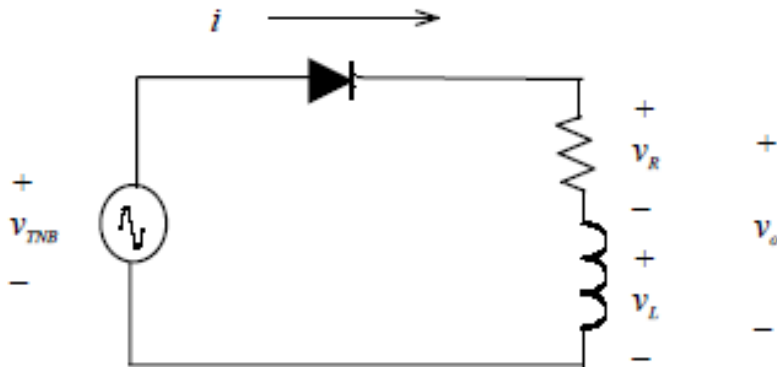
$$V_o = V_{avg} = V_{DC} = \frac{1}{2\pi} \int_0^{\pi} V_m \sin(\omega t) d\omega t$$
$$= \frac{V_m}{\pi} = 0.318V_m$$

DC izlazni napon

$$V_{o,rms} = \sqrt{\frac{1}{2\pi} \int_0^{\pi} (V_m \sin \omega t)^2 d\omega t} = 0.5V_m$$

RMS izlazni napon

IDEALNI POLUTALSANI ISPRAVLJAČ: MONOFAZNI, R-L OPTEREĆENJE



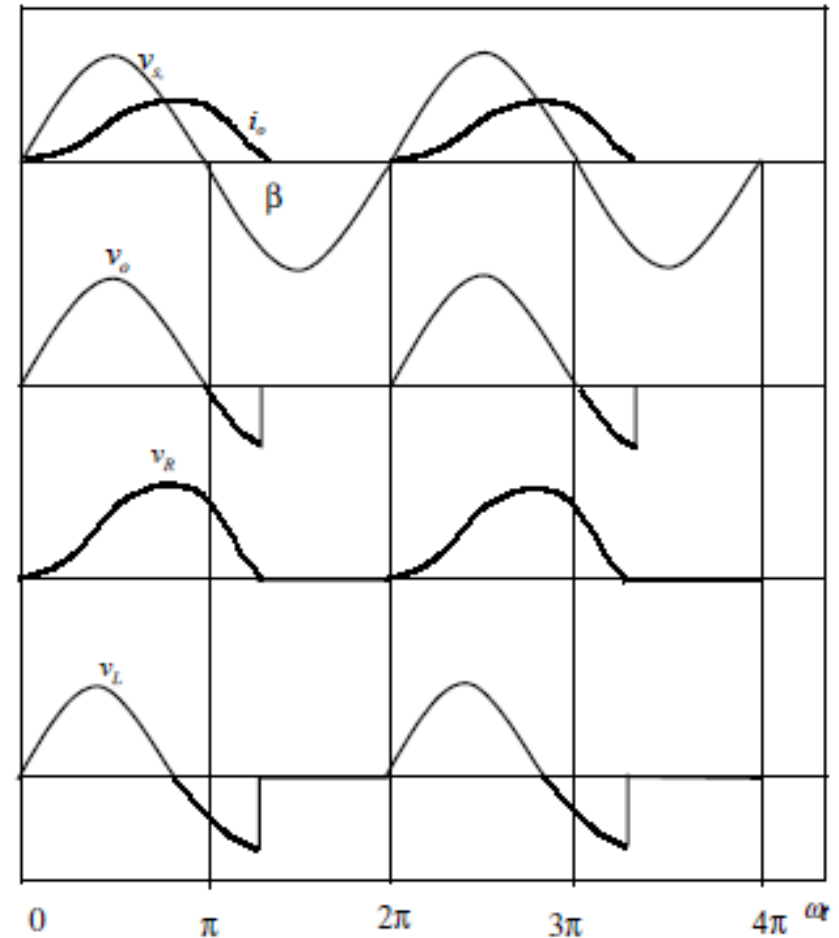
$$v_s = v_R + v_L$$

$$V_m \sin(\omega t) = i(t)R + L \frac{di(t)}{dt}$$

$$i(\omega t) = \begin{cases} \left(\frac{V_m}{Z} \right) \cdot [\sin(\omega t - \theta) + \sin(\theta) e^{-\omega t / \omega \tau}] & \text{za } 0 \leq \omega t \leq \beta \\ 0 & \text{za } 2\pi > \omega t > \beta \end{cases}$$

$$\theta = \tan^{-1} \left(\frac{\omega L}{R} \right)$$

$$\tau = L/R$$

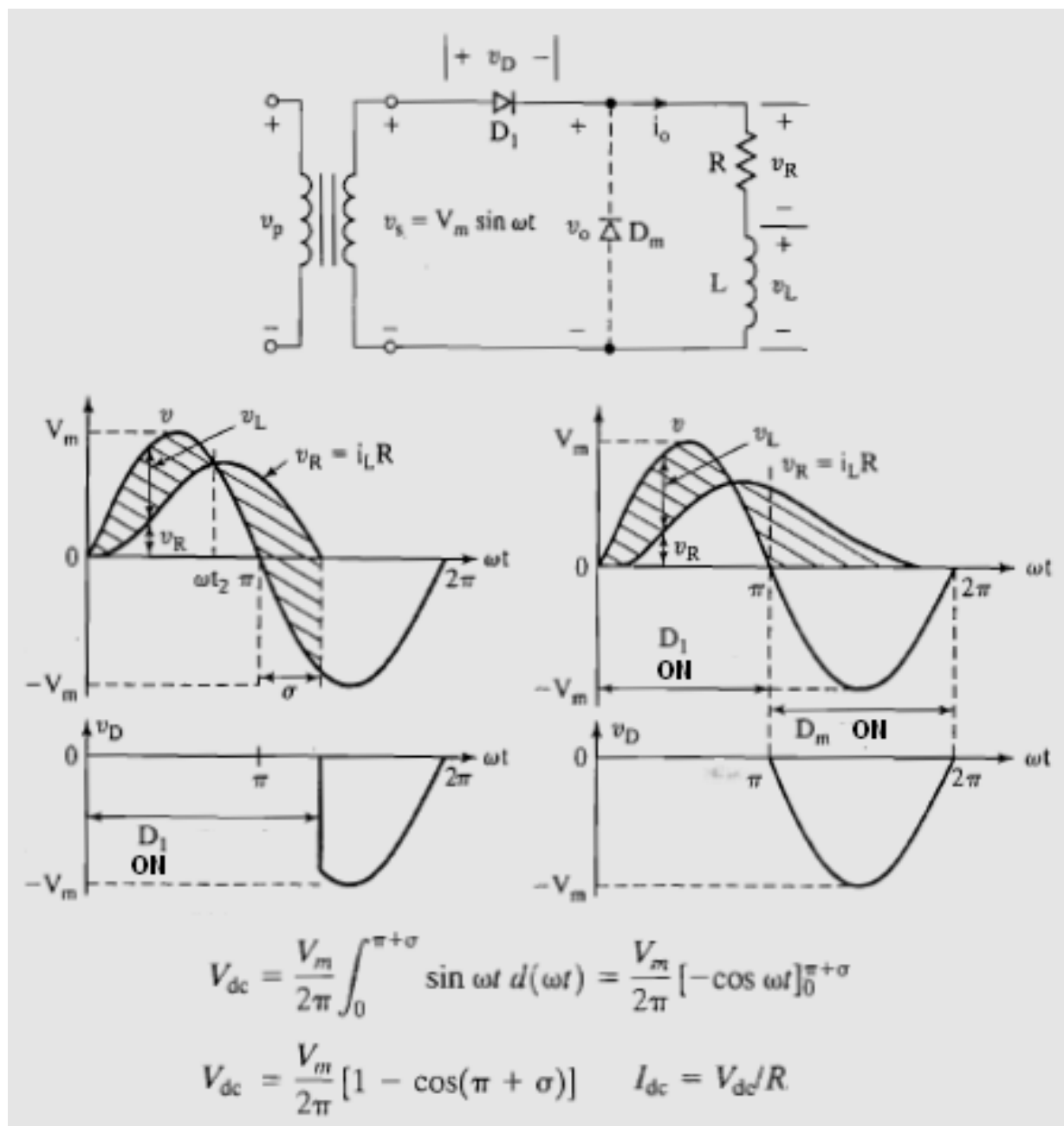


UGAO β ODREĐUJEMO IZ USLOVA:

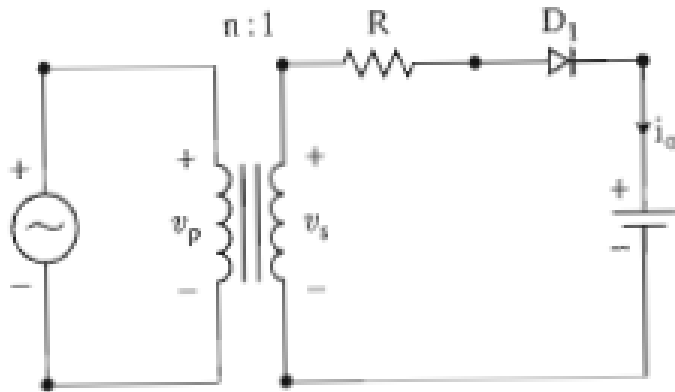
$$i(\beta) = \left(\frac{V_m}{Z} \right) \cdot [\sin(\beta - \theta) + \sin(\theta) e^{-\beta / \omega \tau}] = 0$$

$$\sin(\beta - \theta) + \sin(\theta) e^{-\beta / \omega \tau} = 0$$

KORIŠĆENJE ZAMAJNE DIODE ZA ELIMINISANJE NEGATIVNOG IZLAZNOG NAPONA



IDEALNI POLUTALSANI ISPRAVLJAČ: MONOFAZNI, OPTEREĆENJE: R-DC izvor (PUNJAČ BATERIJE SA PREDOTPOROM)

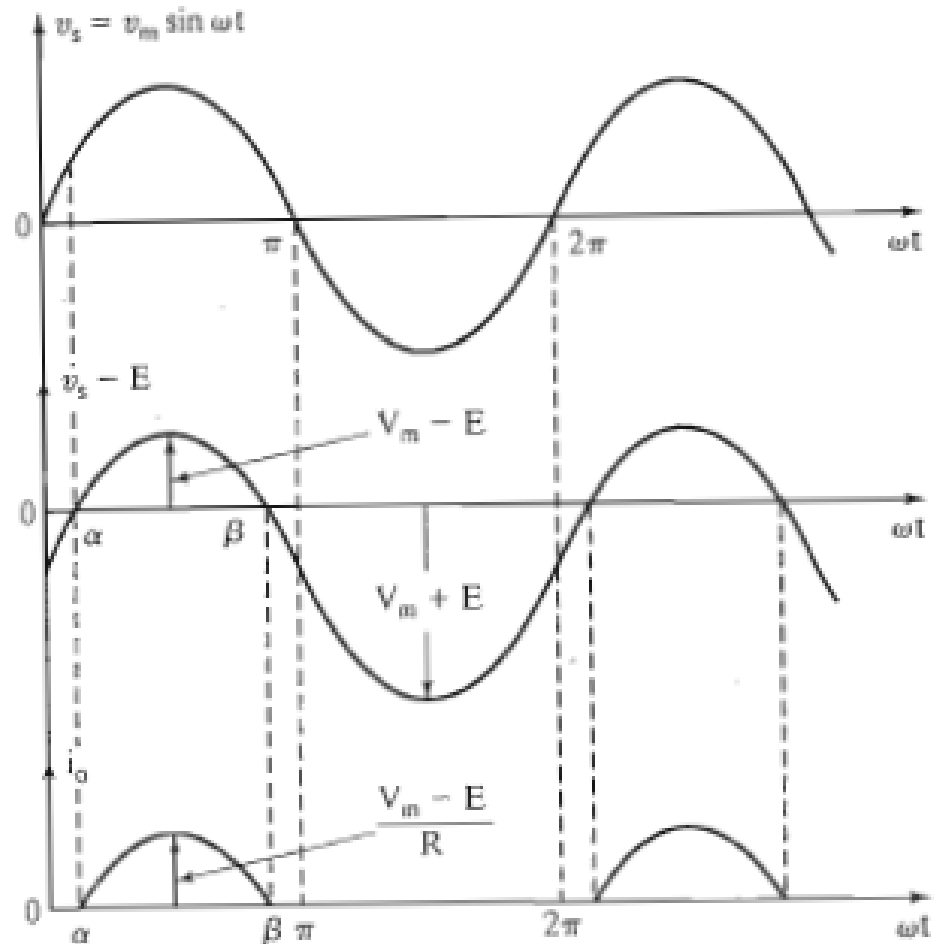


$$V_m \sin \alpha = E \quad \alpha = \sin^{-1} \frac{E}{V_m}$$

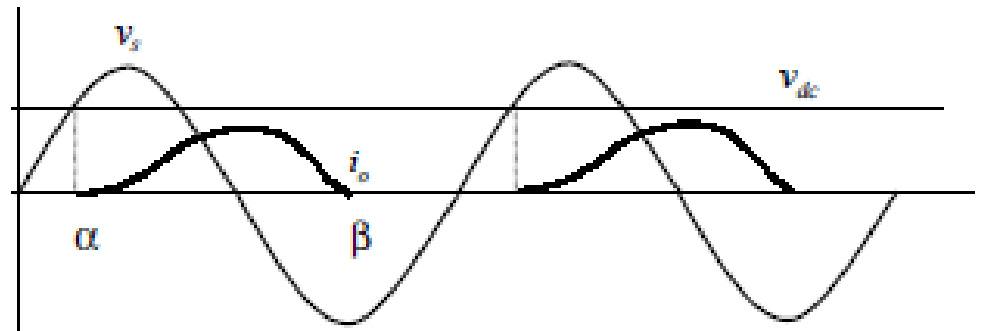
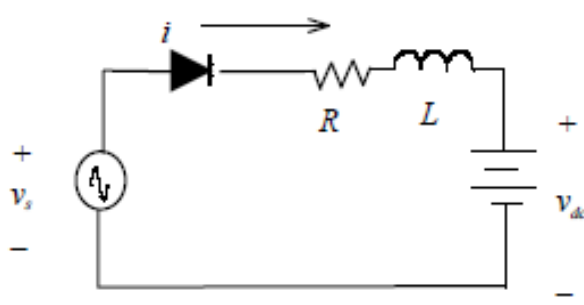
$$\beta = \pi - \alpha$$

$$i_o = \frac{v_s - E}{R} = \frac{V_m \sin \omega t - E}{R}$$

$$\alpha < \omega t < \beta$$



IDEALNI POLUTALSANI ISPRAVLJAČ: MONOFAZNI, OPTEREĆENJE: R-L –DC izvor



Početak vođenja diode

$$V_m \sin \omega t = iR(t) + L \frac{di(t)}{dt} + V_{dc}$$

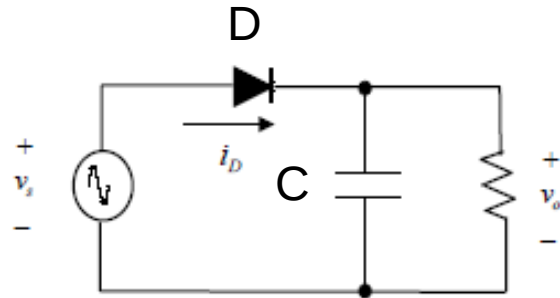
$$V_m \sin \alpha = V_{dc} \Rightarrow \alpha = \sin^{-1} \left(\frac{V_{dc}}{V_m} \right)$$

$$V_m \sin \omega t = iR(t) + L \frac{di(t)}{dt} + V_{dc}$$

$$i(\omega t) = \begin{cases} \left(\frac{V_m}{Z} \right) \cdot \left[\sin(\omega t - \theta) - \frac{V_{dc}}{R} + A e^{-\omega t / \omega \tau} \right] & \text{za } \alpha \leq \omega t \leq \beta \\ 0 & \text{za } 2\pi + \alpha > \omega t > \beta \end{cases}$$

$$A = \left(\frac{V_m}{Z} \sin(\alpha - \theta) + \frac{V_{dc}}{R} \right) e^{\alpha / \omega \tau}$$

IDEALNI POLUTALSANI ISPRAVLJAČ: MONOFAZNI, OPTEREĆENJE: R-C



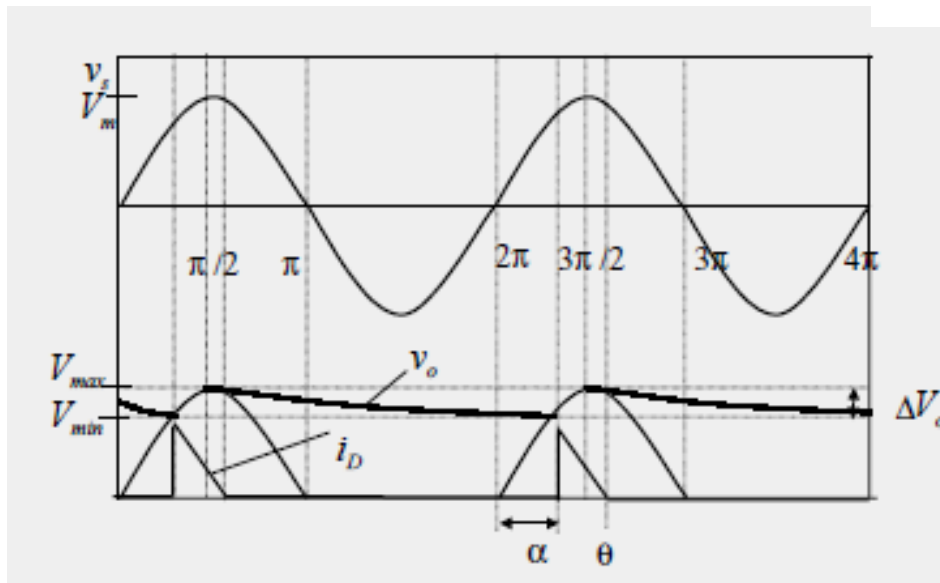
$$v_o = \begin{cases} V_m \sin(\omega t) & \text{D on} \\ V_\theta e^{-(\omega t - \theta)/\omega RC} & \text{D off} \end{cases}$$

$$V_\theta = V_m \sin \theta$$

$$V_\theta = V_m \quad \theta = \pi/2 \quad \alpha \approx \pi/2$$

$$\Delta V_o = V_{\max} - V_{\min} = V_m - V_m \sin(2\pi + \alpha) = V_m - V_m \sin \alpha$$

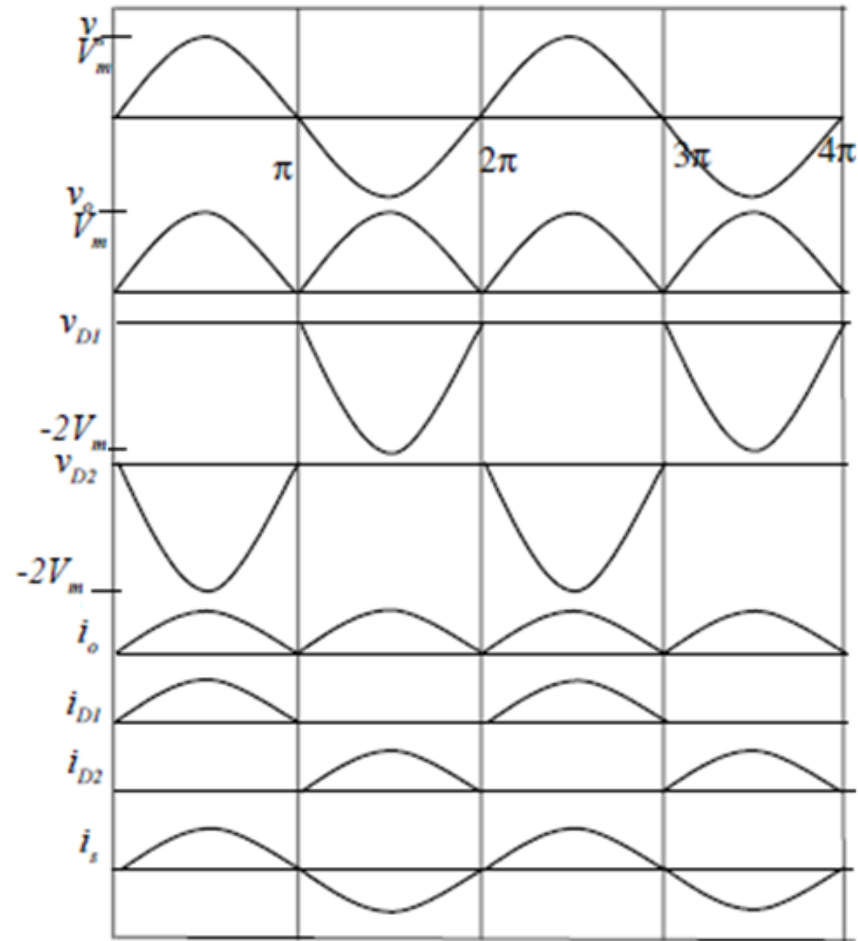
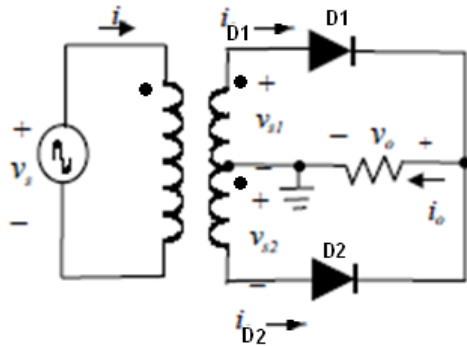
$$v_o(2\pi + \alpha) = V_m e^{-\left(\frac{2\pi + \pi/2 - \pi/2}{\omega RC}\right)} = V_m e^{-\left(\frac{2\pi}{\omega RC}\right)} \quad \Delta V_o \approx V_m - V_m e^{-\left(\frac{2\pi}{\omega RC}\right)} = V_m \left(1 - e^{-\left(\frac{2\pi}{\omega RC}\right)}\right)$$

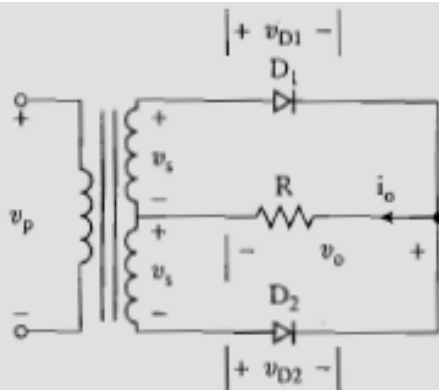


$$1 - e^{-\left(\frac{2\pi}{\omega RC}\right)} = 1 - \frac{2\pi}{\omega RC}$$

$$\Delta V_o = V_m \left(\frac{2\pi}{\omega RC}\right) = \frac{V_m}{fRC}$$

IDEALNI PUNOTALSANI SPRAVLJAČ : MONOFAZNI, OPTEREČENJE: R (TALASNI OBLICI)





$$V_{dc} = \frac{2}{T} \int_0^{T/2} V_m \sin \omega t \, dt = \frac{2V_m}{\pi} = 0.6366V_m$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{0.6366V_m}{R} \quad P_{dc} = (0.6366V_m)^2/R$$

$$V_{rms} = \left[\frac{2}{T} \int_0^{T/2} (V_m \sin \omega t)^2 \, dt \right]^{1/2} = \frac{V_m}{\sqrt{2}} = 0.707V_m$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{0.707V_m}{R} \quad P_{ac} = (0.707V_m)^2/R$$

EFIKASHOST $\eta = (0.6366V_m)^2 / (0.707V_m)^2 = 81\%$

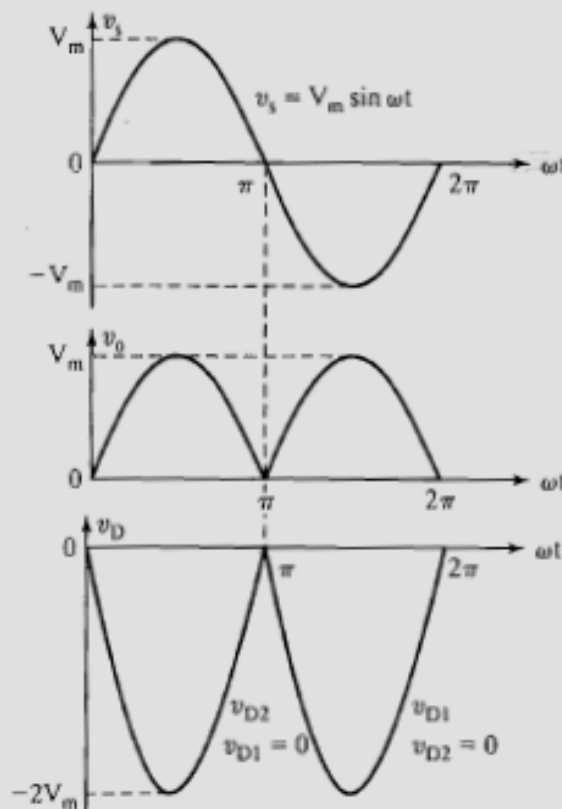
FORM FACTOR (Faktor Oblika) $FF = 0.707V_m / 0.6366V_m = 1.11$

RIPPLE FACTOR $RF = \sqrt{1.11^2 - 1} = 0.482$ or 48.2%

MAX INV. diode $PIV = 2V_m$

POWER FACTOR $PF = \frac{P_{dc}}{VA} = \frac{0.707^2}{2 \times 0.707 \times 0.5} = 0.707$
(PF)-faktor snage

$$1/TUF = 1/0.5732 = 1.75$$



TRANSFORMATOR

$$V_s = V_m / \sqrt{2} = 0.707V_m$$

$$I_s = 0.5V_m/R$$

$$VA = 2V_s I_s = 2 \times 0.707V_m \times 0.5V_m/R$$

$$TUF = \frac{P_{dc}}{VA} = \frac{0.6366^2}{2 \times 0.707 \times 0.5} = 0.5732 = 57.32\%$$

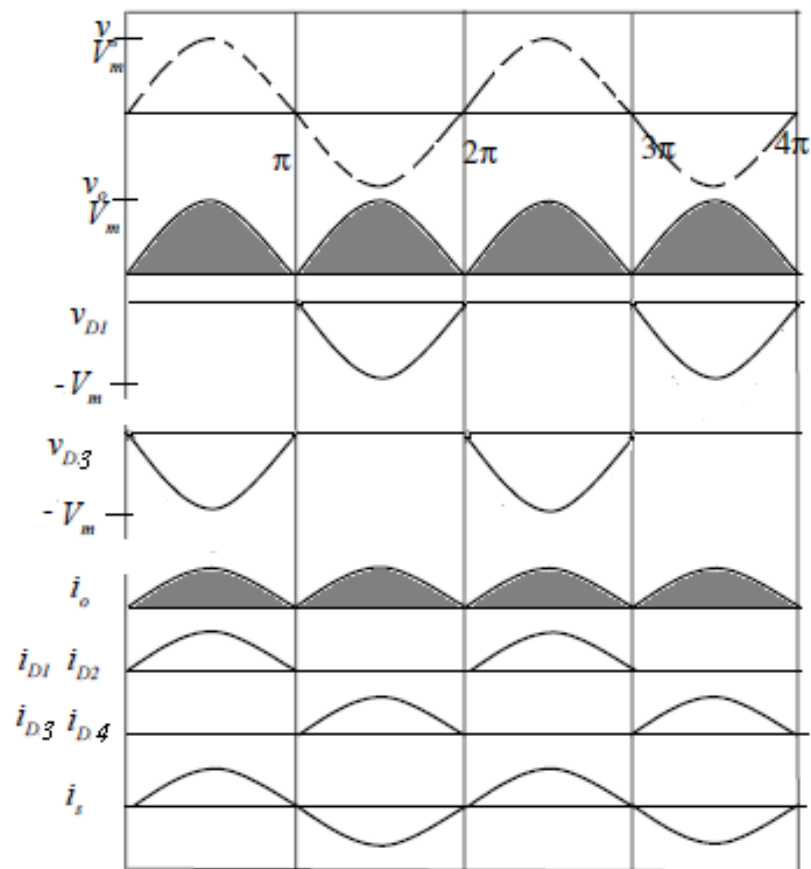
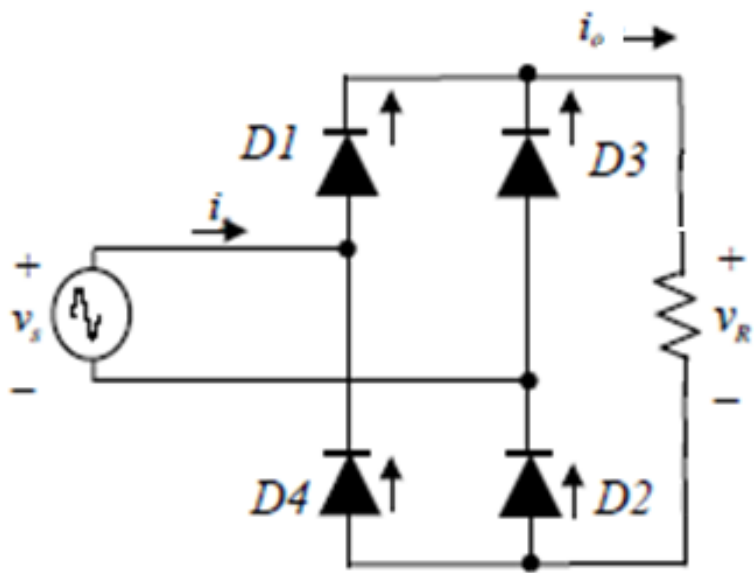
$$I_{s(peak)} = V_m/R$$

$$I_s = 0.707V_m/R$$

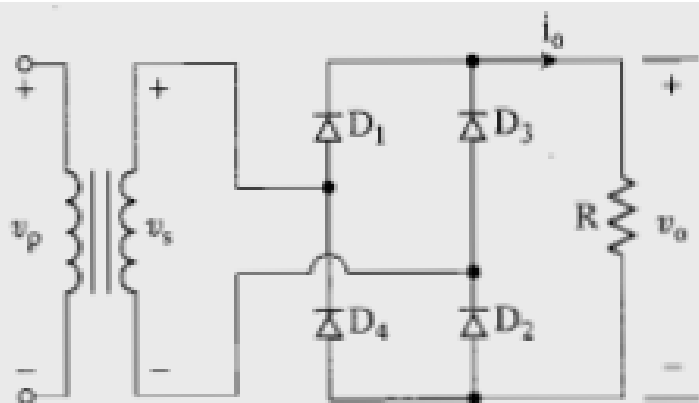
$$CF = I_{s(peak)} / I_s = 1/0.707 = \sqrt{2}$$

Ovaj transformator mora biti 1.75 puta predimenzionisan u odnosu na klasični sa AC ulazom i izlazom

IDEALNI PUNOTALSANI SPRAVLJAČ U GRECOVOM SPOJU: MONOFAZNI, OPTEREĆENJE: R (TALASNI OBLICI)



IDEALNI PUNOTALSANI SPRAVLJAČ U GRECOVOM SPOJU: PRORAČUNI

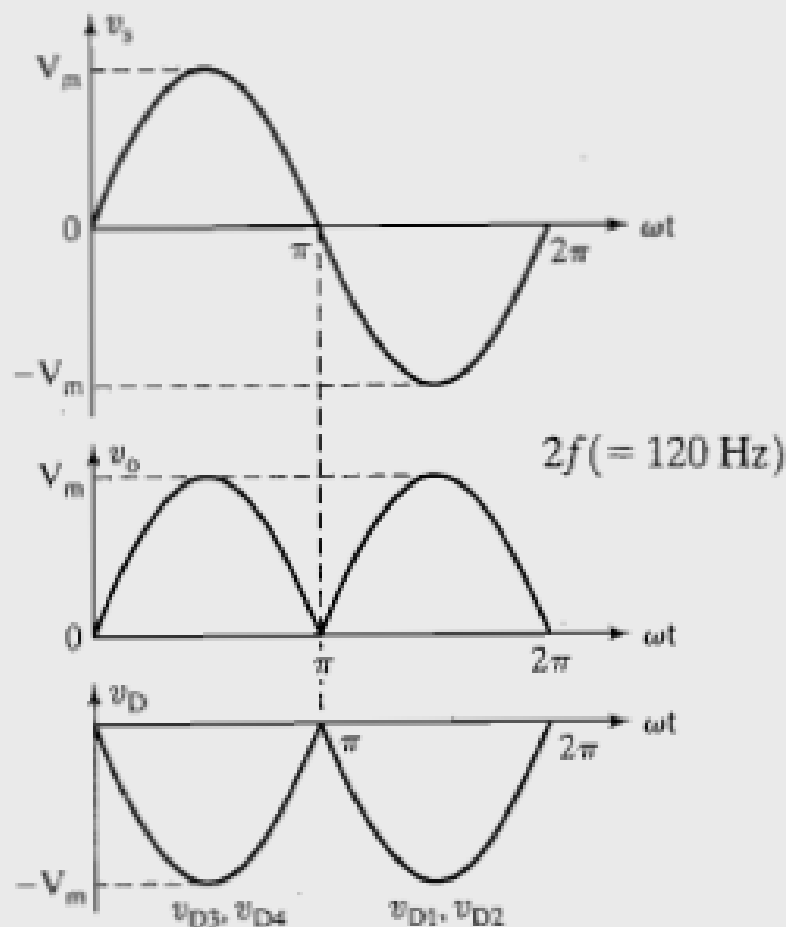


$$V_{dc} = \frac{2}{T} \int_0^{T/2} V_m \sin \omega t \, dt = \frac{2V_m}{\pi} = 0.6366V_m$$

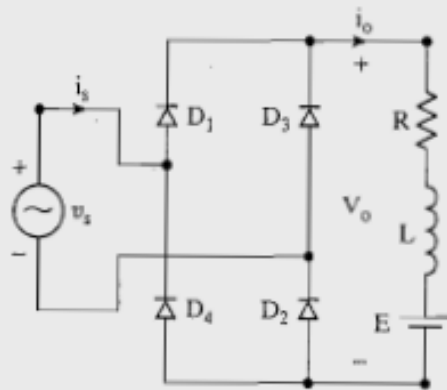
$$I_{dc} = \frac{V_{dc}}{R} = \frac{0.6366V_m}{R} \quad P_{dc} = (0.6366V_m)^2/R$$

$$V_{rms} = \left[\frac{2}{T} \int_0^{T/2} (V_m \sin \omega t)^2 \, dt \right]^{1/2} = \frac{V_m}{\sqrt{2}} = 0.707V_m$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{0.707V_m}{R} \quad P_{ac} = (0.707V_m)^2/R$$



IDEALNI PUNOTALSANI SPRAVLJAČ U GRECOVOM SPOJU: MONOFAZNI, OPTEREĆENJE: R –L-DC izvor (tipična primena za punjače baterija)



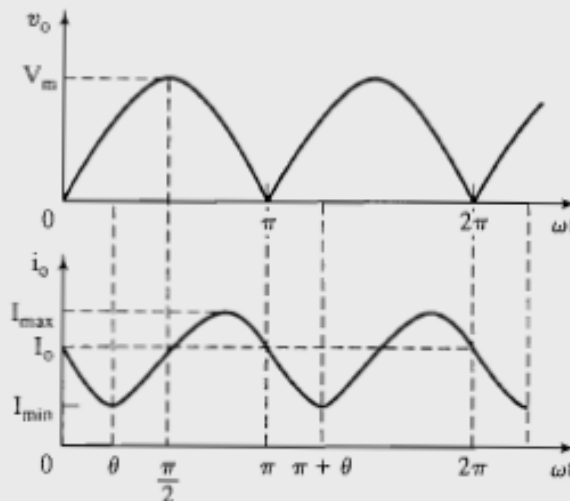
$$L \frac{di_o}{dt} + Ri_o + E = \sqrt{2} V_s \sin \omega t$$

$$i_o \geq 0$$

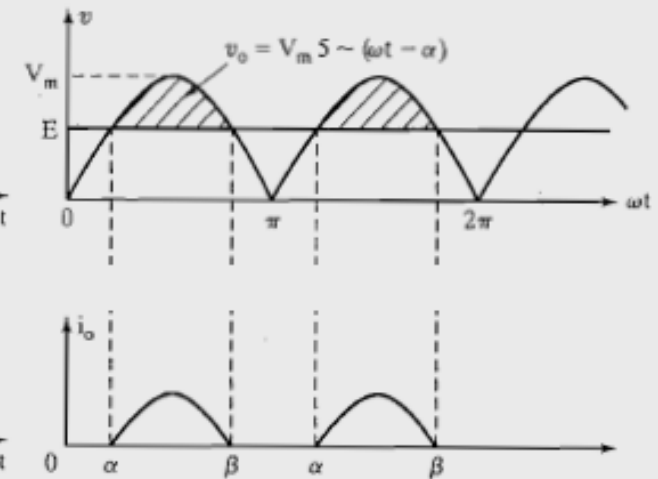
$$i_o = \frac{\sqrt{2} V_s}{Z} \sin(\omega t - \theta) + A_1 e^{-(R/L)t} - \frac{E}{R}$$

$$Z = [R^2 + (\omega L)^2]^{1/2}$$

$$\theta = \tan^{-1}(\omega L/R)$$



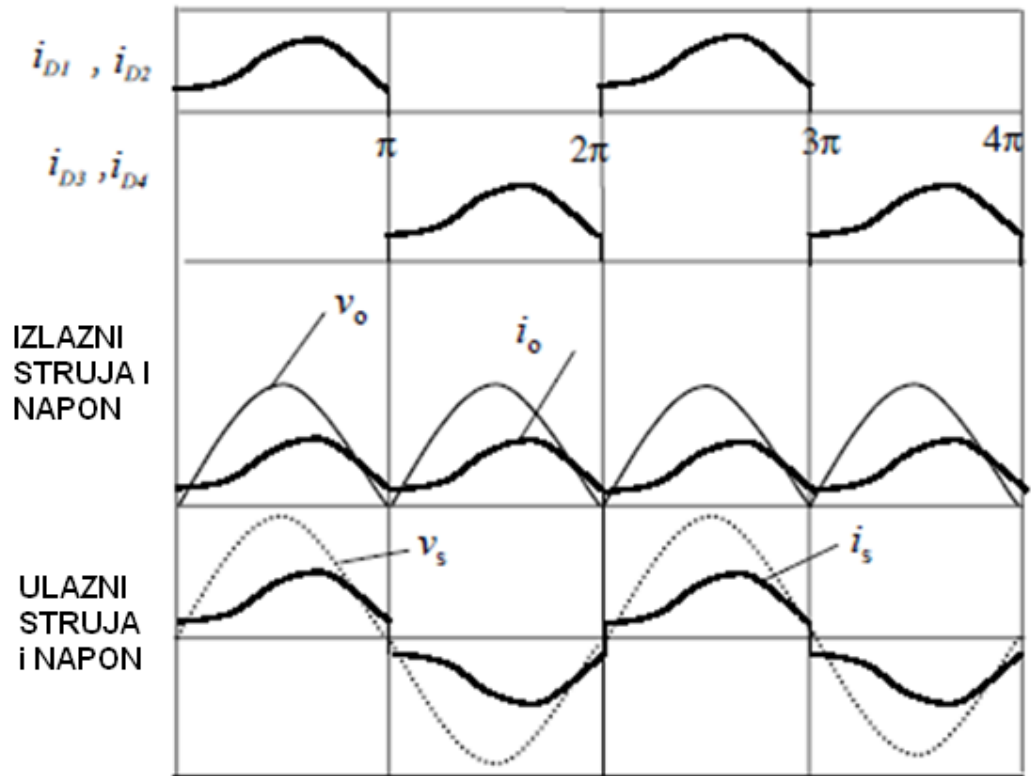
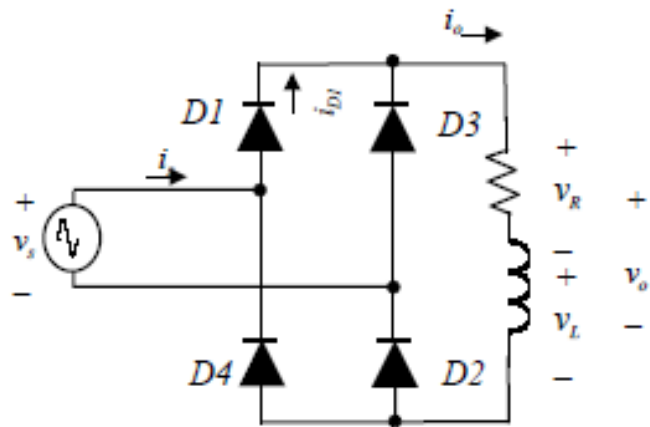
KONTINUALNI
REZIM $\omega L/R \gg 1$



DISKONTINUALNI (PREKIDNI)
REZIM

$$\omega L/R \approx 1$$

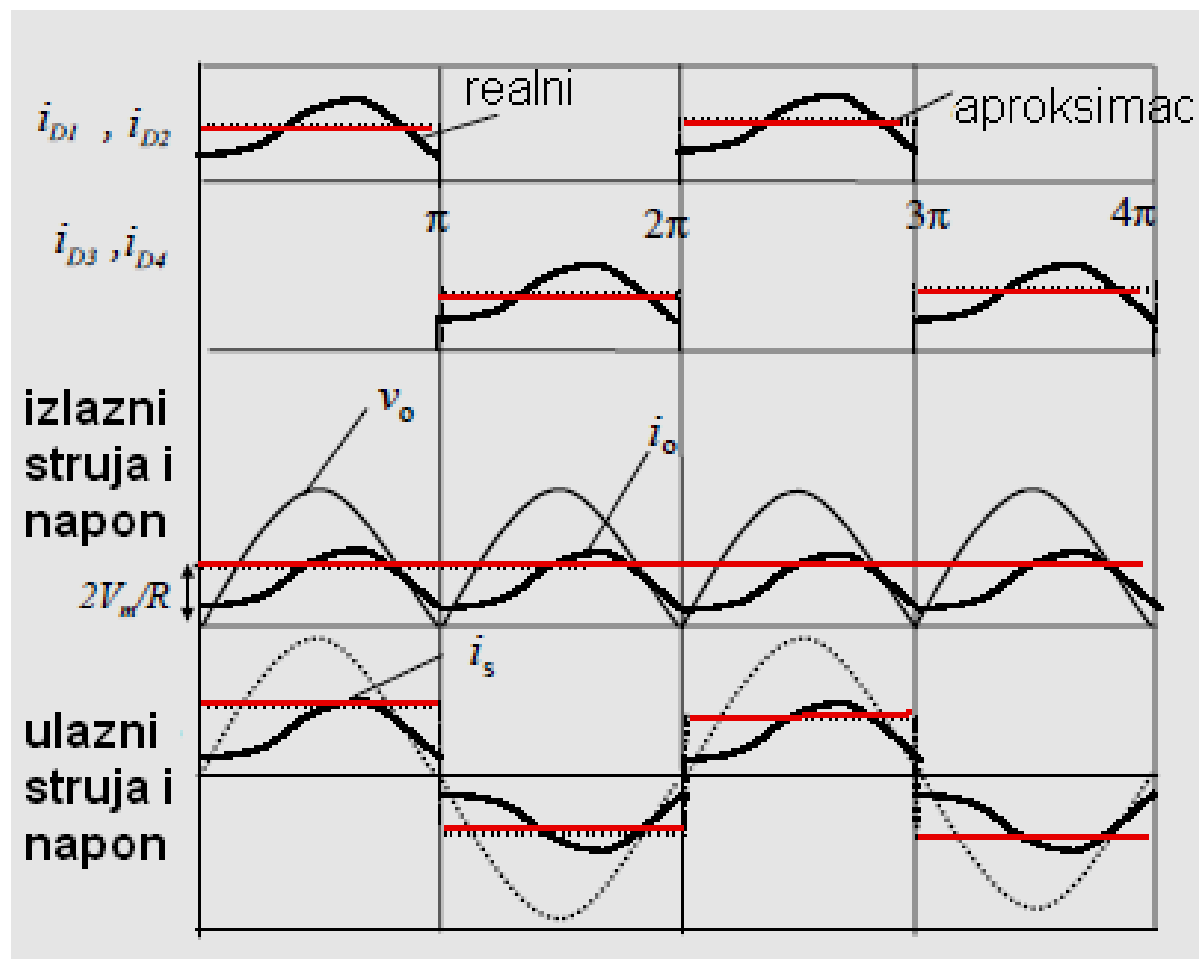
IDEALNI PUNOTALSANI SPRAVLJAČ: MONOFAZNI, OPTEREĆENJE: R -L



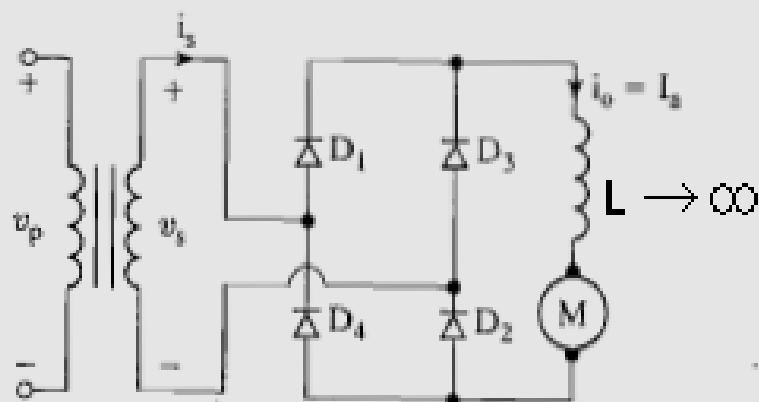
IDEALNI PUNOTALSANI SPRAVLJAČ: MONOFAZNI, OPTEREĆENJE: JAKO INDUKTIVNO

$$i(\omega t) \approx I_o = \frac{V_o}{R} = \frac{2V_m}{R},$$

$$\omega L \gg R,$$



IDEALNI PUNOTALSANI SPRAVLJAČ: MONOFAZNI, OPTEREĆENJE: PRETEŽNO INDUKTIVNO (DC MOTOR SA VELIKOM REDNOM PRIGUŠNICOM)



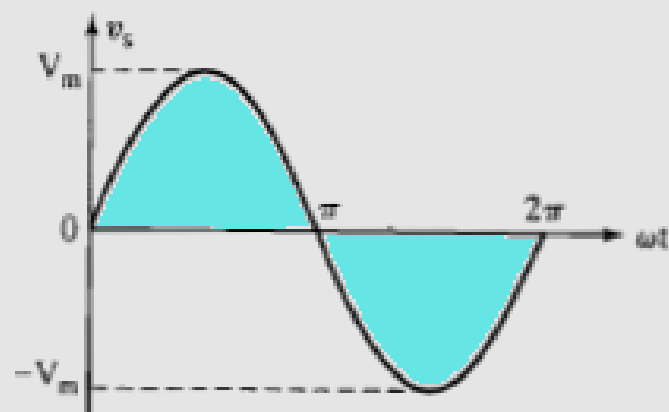
$$i_s(t) = \frac{4I_a}{\pi} \left(\frac{\sin \omega t}{1} + \frac{\sin 3\omega t}{3} + \frac{\sin 5\omega t}{5} + \dots \right)$$

$$I_{s1} = \frac{4I_a}{\pi\sqrt{2}} = 0.90I_a$$

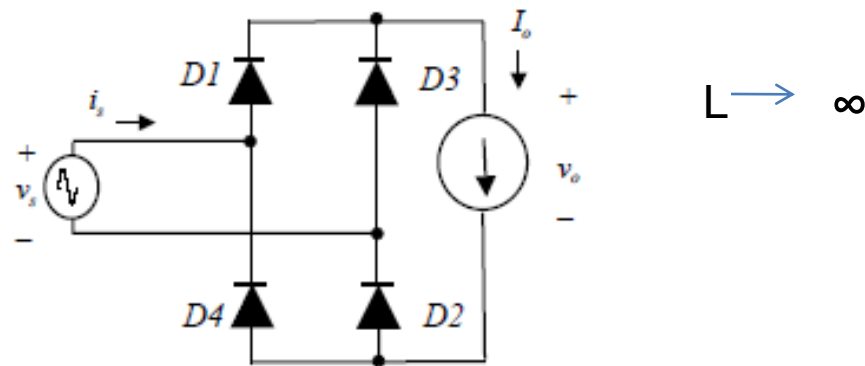
$$I_s = \frac{4}{\pi\sqrt{2}} I_a \left[1 + \left(\frac{1}{3} \right)^2 + \left(\frac{1}{5} \right)^2 + \left(\frac{1}{7} \right)^2 + \left(\frac{1}{9} \right)^2 + \dots \right]^{1/2} = I_a$$

$$\text{PF} = (I_{s1}/I_s) \cos \phi = 0.90 \quad \text{DF} = \cos \phi = 1$$

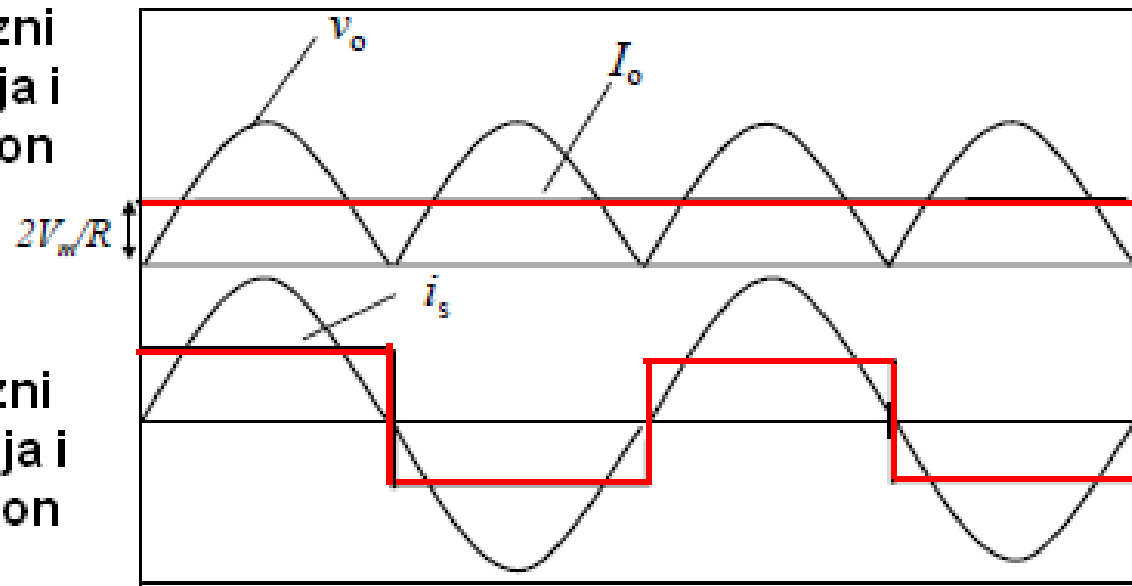
$$\text{HF} = \text{THD} = \left[\left(\frac{1}{0.90} \right)^2 - 1 \right]^{1/2} = 0.4843$$



IDEALNI PUNOTALSANI SPRAVLJAČ: MONOFAZNI, OPTEREĆENJE: STRUJNI PONOR

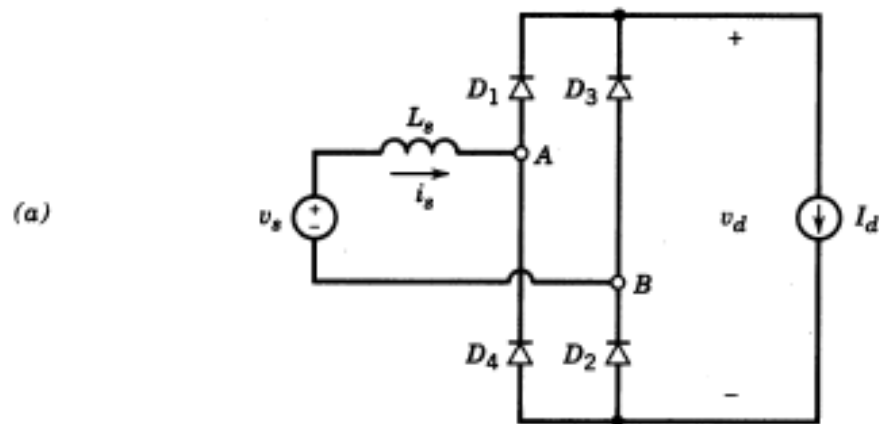


izlazni
struja i
napon

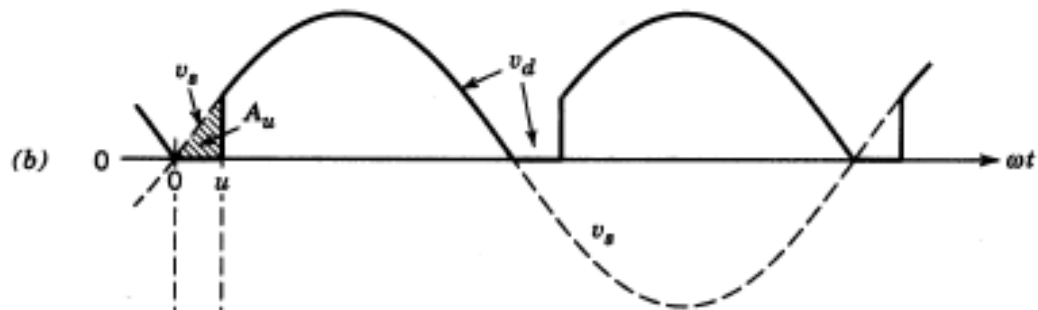


ulazni
struja i
napon

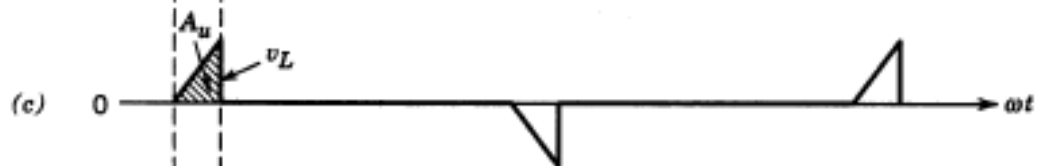
EFEKAT RASIPNE INDUKTIVNOSTI L_s



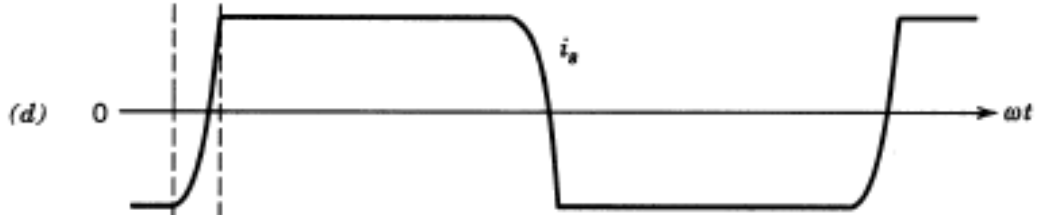
(a)-električna šema



(b)-izlazni napon

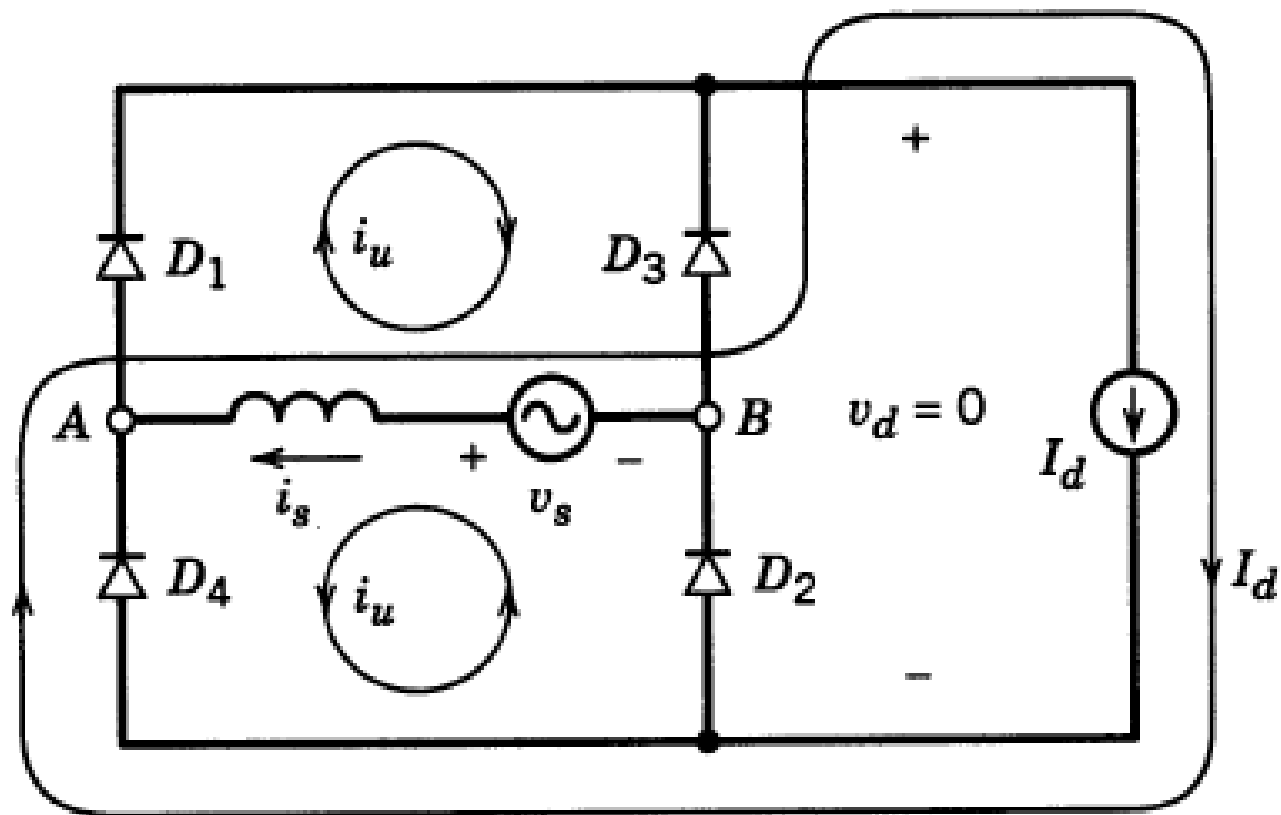


(c)- napon na L_s

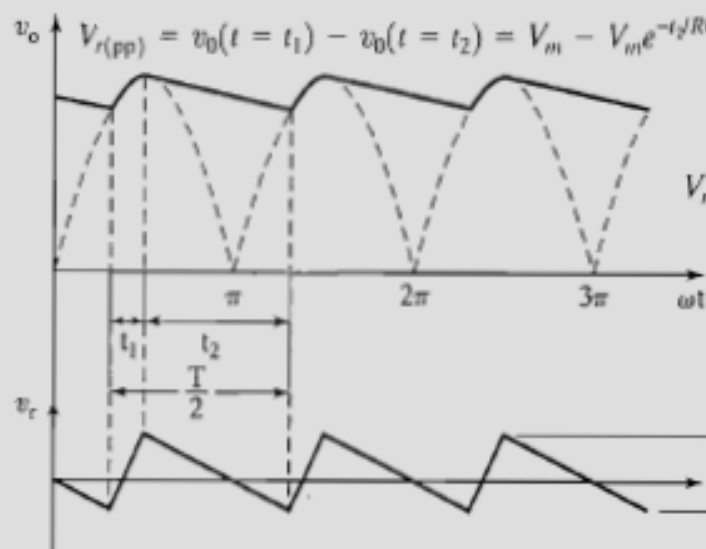
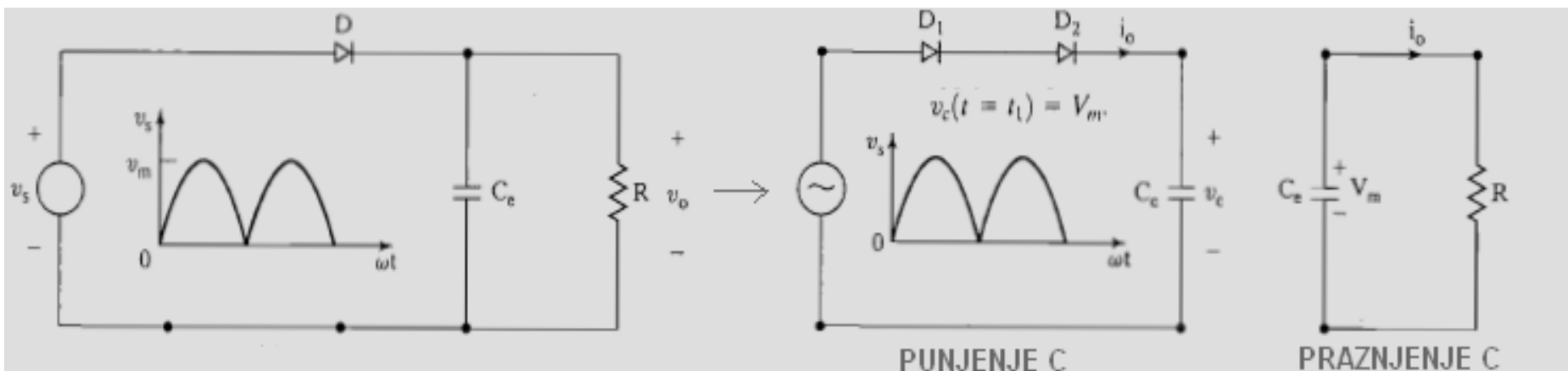


(d)- struja L_s

EFEKAT RASIPNE INDUKTIVNOSTI L_s - kolo za analizu



PUNOTALSNI ISPRAVLJAČ SA KAPACITIVNIM FILTROM



$$V_{r(pp)} = v_o(t = t_1) - v_o(t = t_2) = V_m - V_m e^{-t_2/RC_e} = V_m(1 - e^{-t_2/RC_e})$$

$$e^{-x} \approx 1 - x$$

$$V_{r(pp)} = V_m \left(1 - 1 + \frac{t_2}{RC_e} \right) = \frac{V_m t_2}{RC_e} = \frac{V_m}{2fRC_e}$$

$$t_2 = 1/2f$$

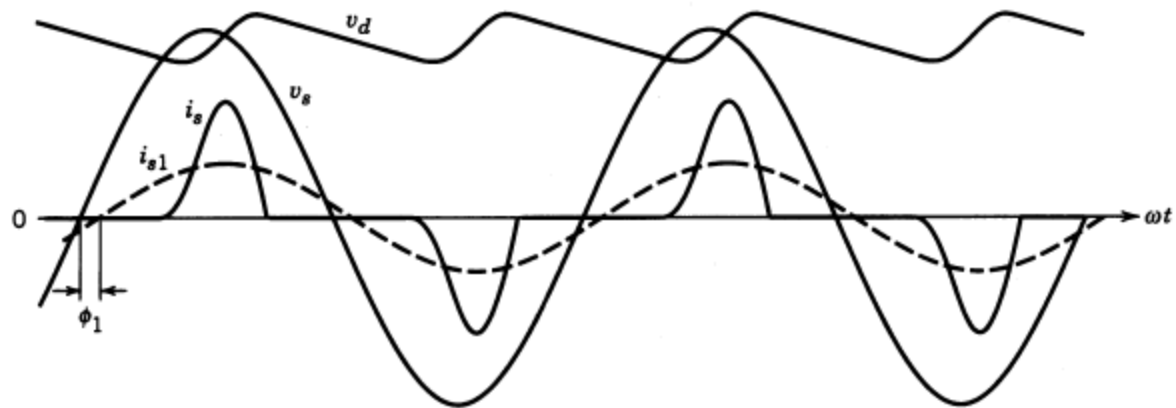
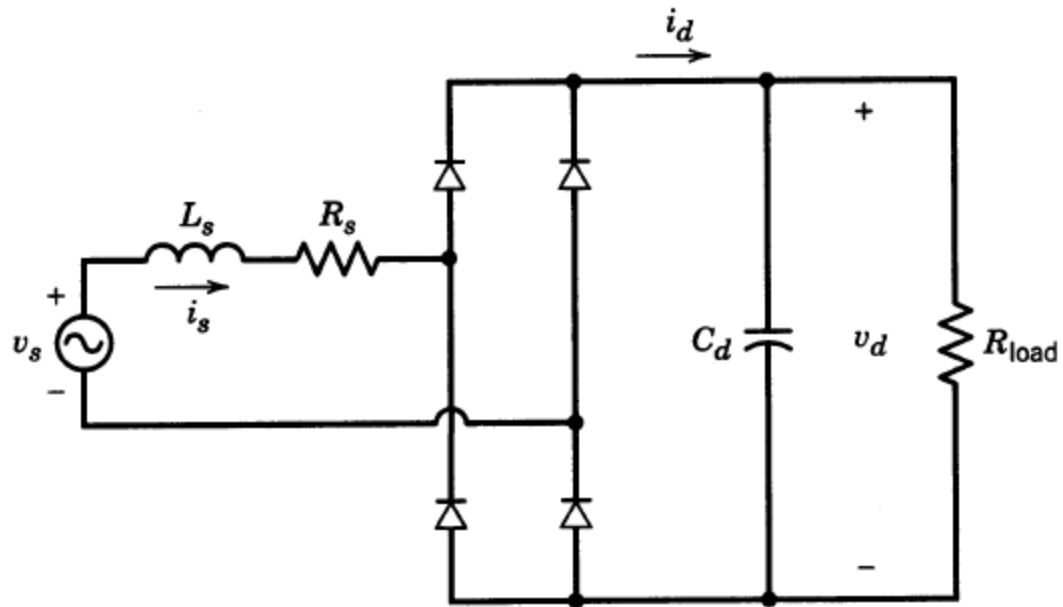
$$V_{dc} = V_m - \frac{V_{r(pp)}}{2} = V_m - \frac{V_m}{4fRC_e}$$

$$V_{ac} = \frac{V_{r(pp)}}{2\sqrt{2}} = \frac{V_m}{4\sqrt{2}fRC_e}$$

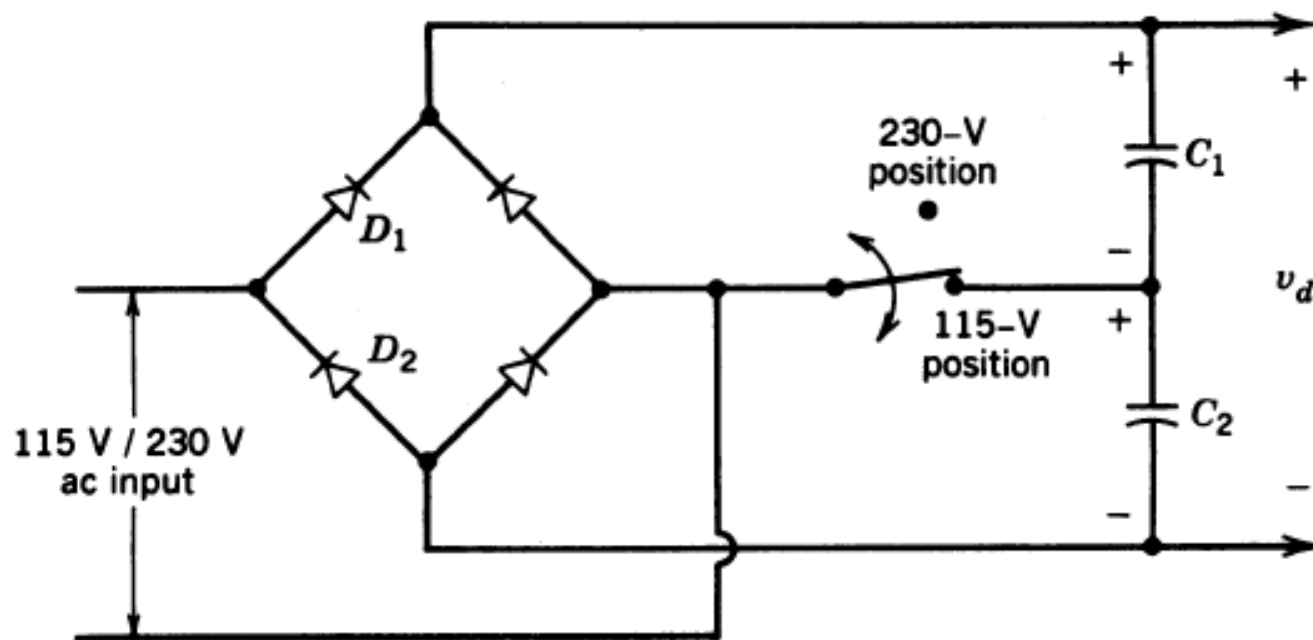
$$RF = \frac{V_{ac}}{V_{dc}} = \frac{V_m}{4\sqrt{2}fRC_e} \frac{4fRC_e}{V_m(4fRC_e - 1)} = \frac{1}{\sqrt{2}(4fRC_e - 1)}$$

$$\begin{aligned} \frac{1}{C_e} \int i_o dt + v_c(t = 0) + Ri_o &= 0 \\ v_c(t = 0) &= V_m \\ i_o &= \frac{V_m}{R} e^{-t/RC_e} \\ v_o(t) &= Ri_o = V_m e^{-t/RC_e} \end{aligned}$$

TALASNI OBLICI REALNOG DIODNOG ISPRAVLJAČA SA RC FILTROM

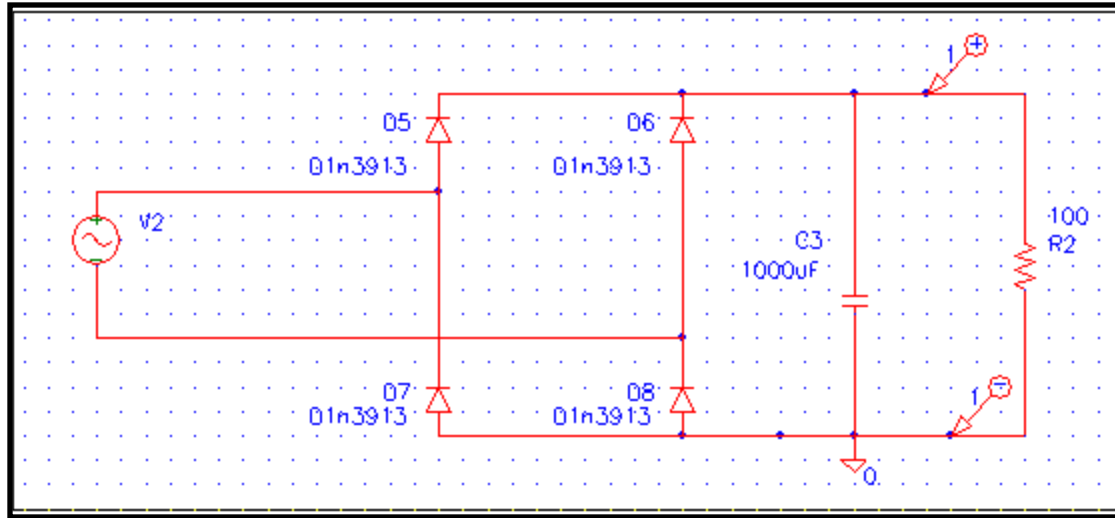


UNIVERZALNI ISPRAVLJAČ SA NAPAJANJEM 110/220V AC

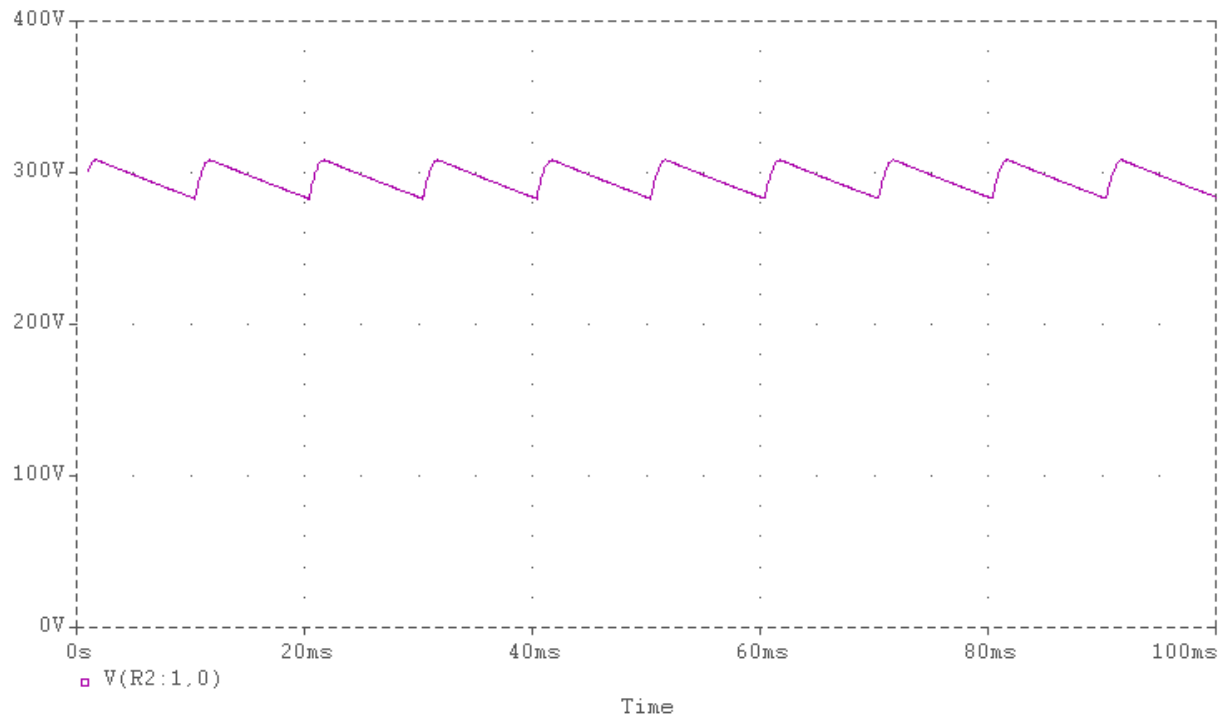


PRIEMENA U MREŽNIM NAPAJANJIMA – *ATX napajanje*

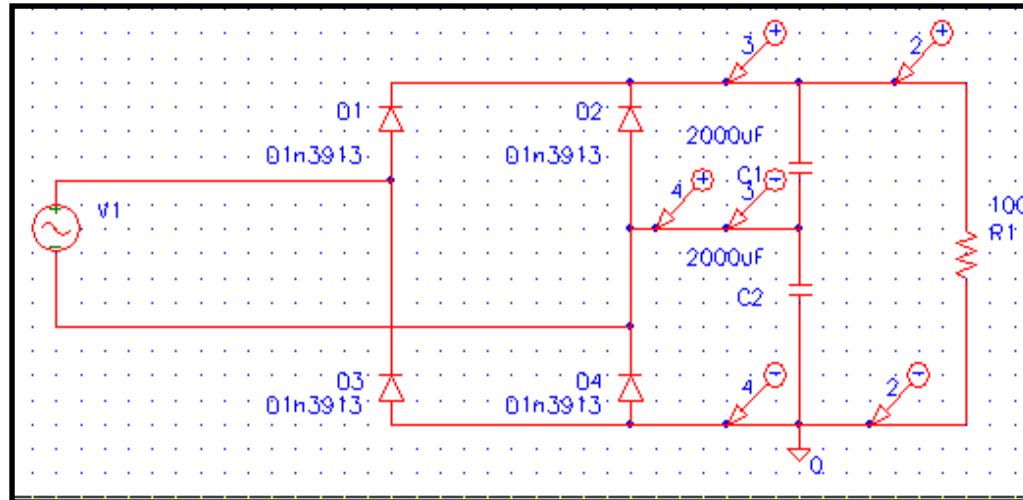
PUNOTALSNI ISPRAVLJAČ U GRECOVOM SPOJU: SIMULACIJA



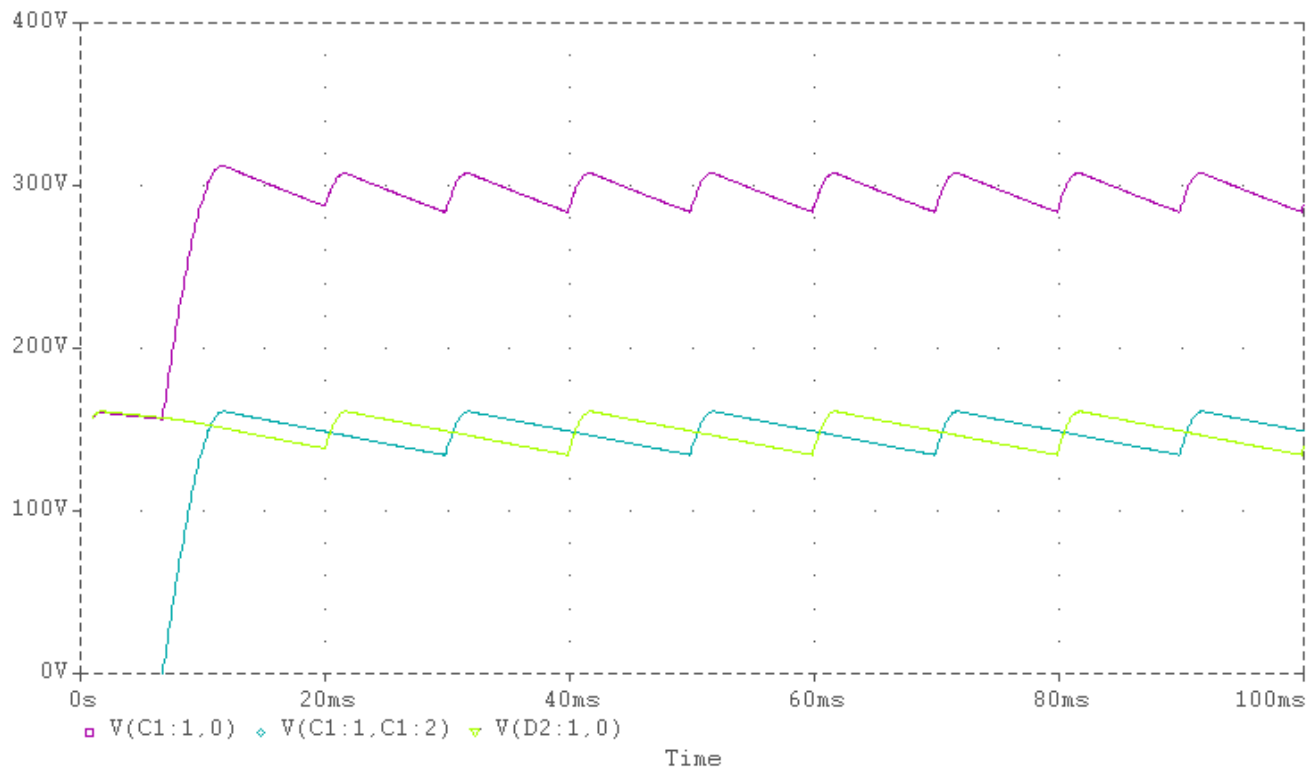
NAPAJANJE
220V,50Hz



PUNOTALSNI ISPRAVLJAČ U GRECOVOM SPOJU: SIMULACIJA

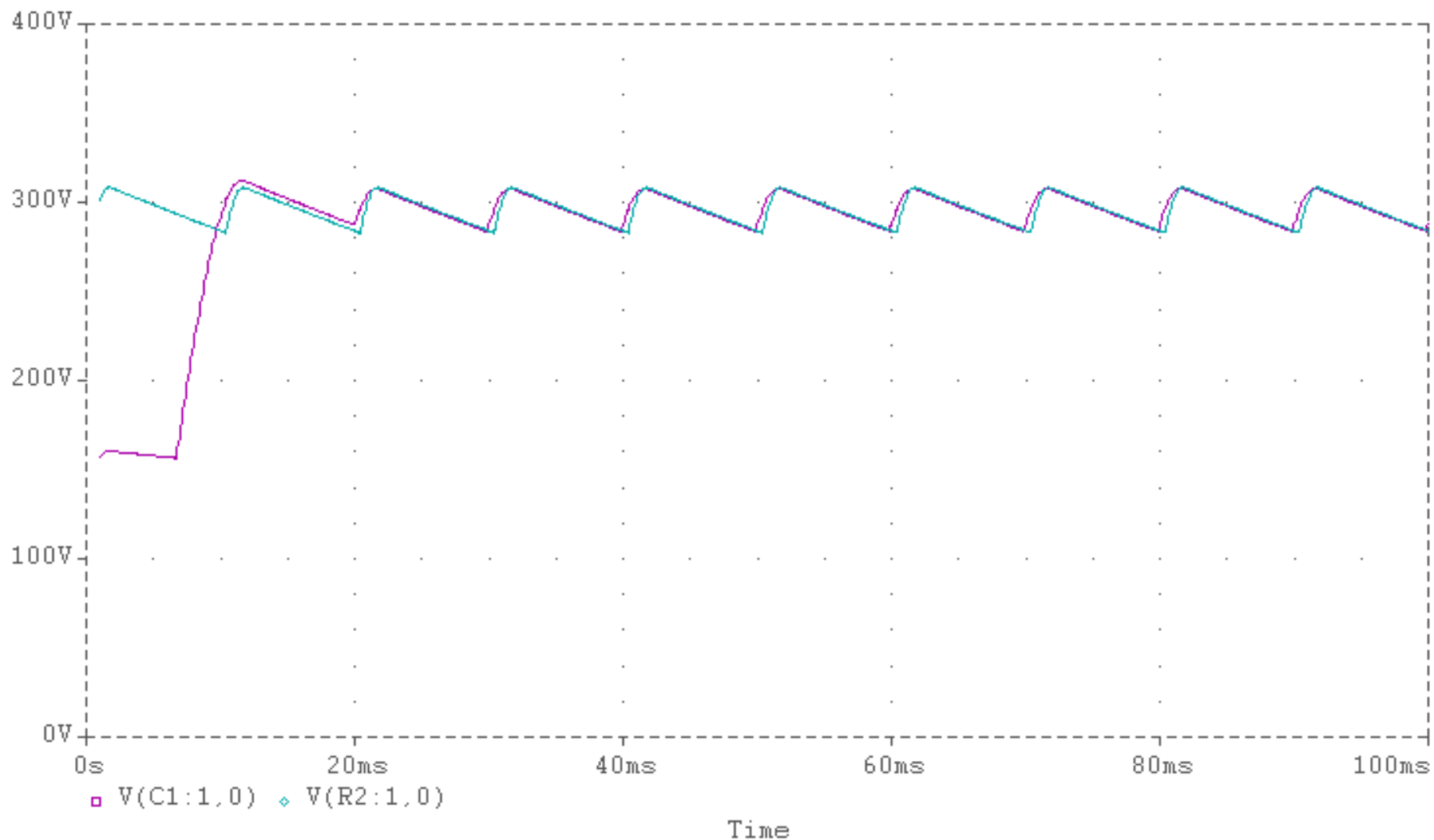


115V, 50Hz
NAPAJANJE



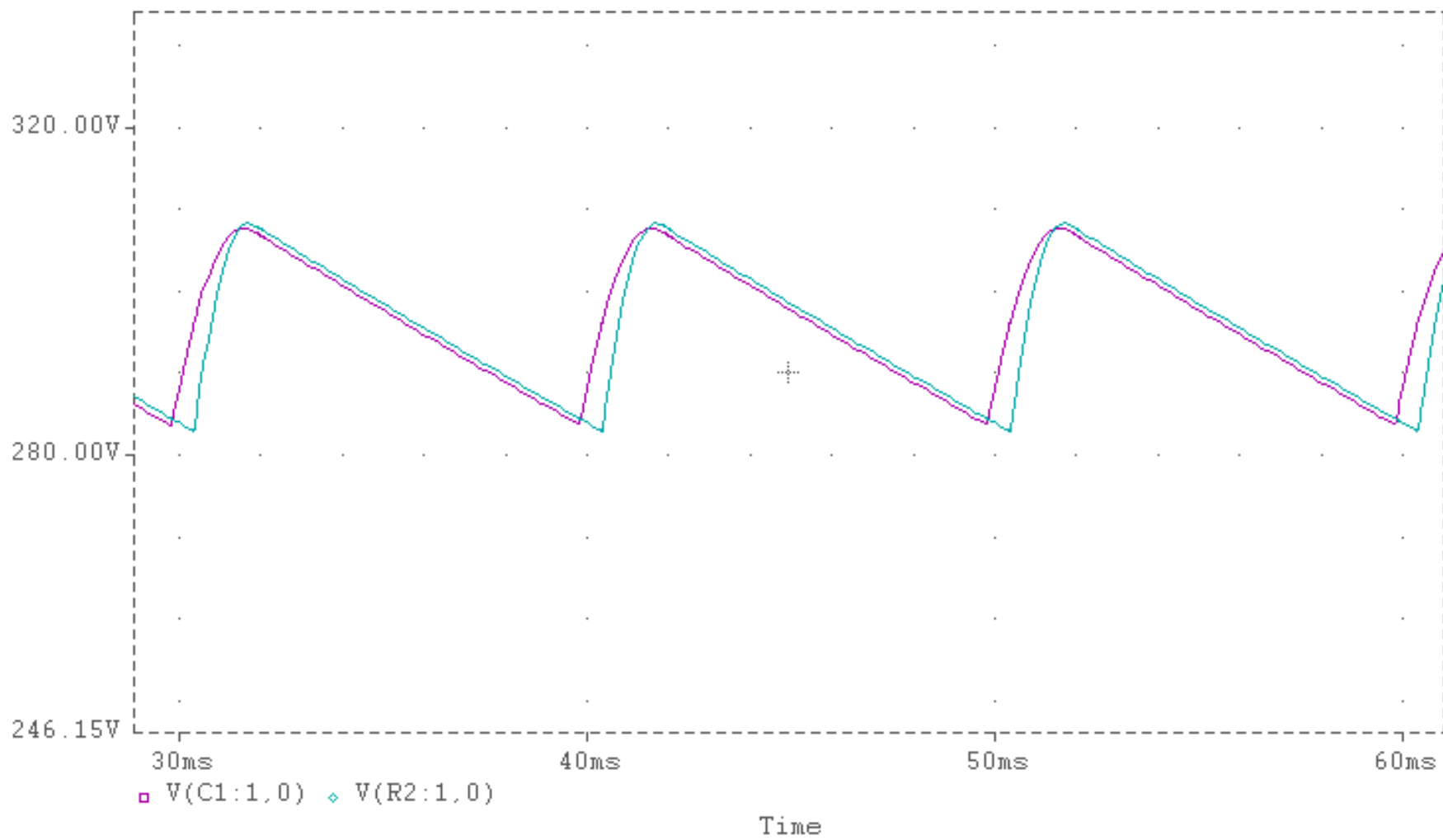
PUNOTALSNI ISPRAVLJAČ U GRECOVOM SPOJU: SIMULACIJA

POREĐENJE IZLAZNOG NAPONA PRI 115V, 50Hz i 230V, 50Hz

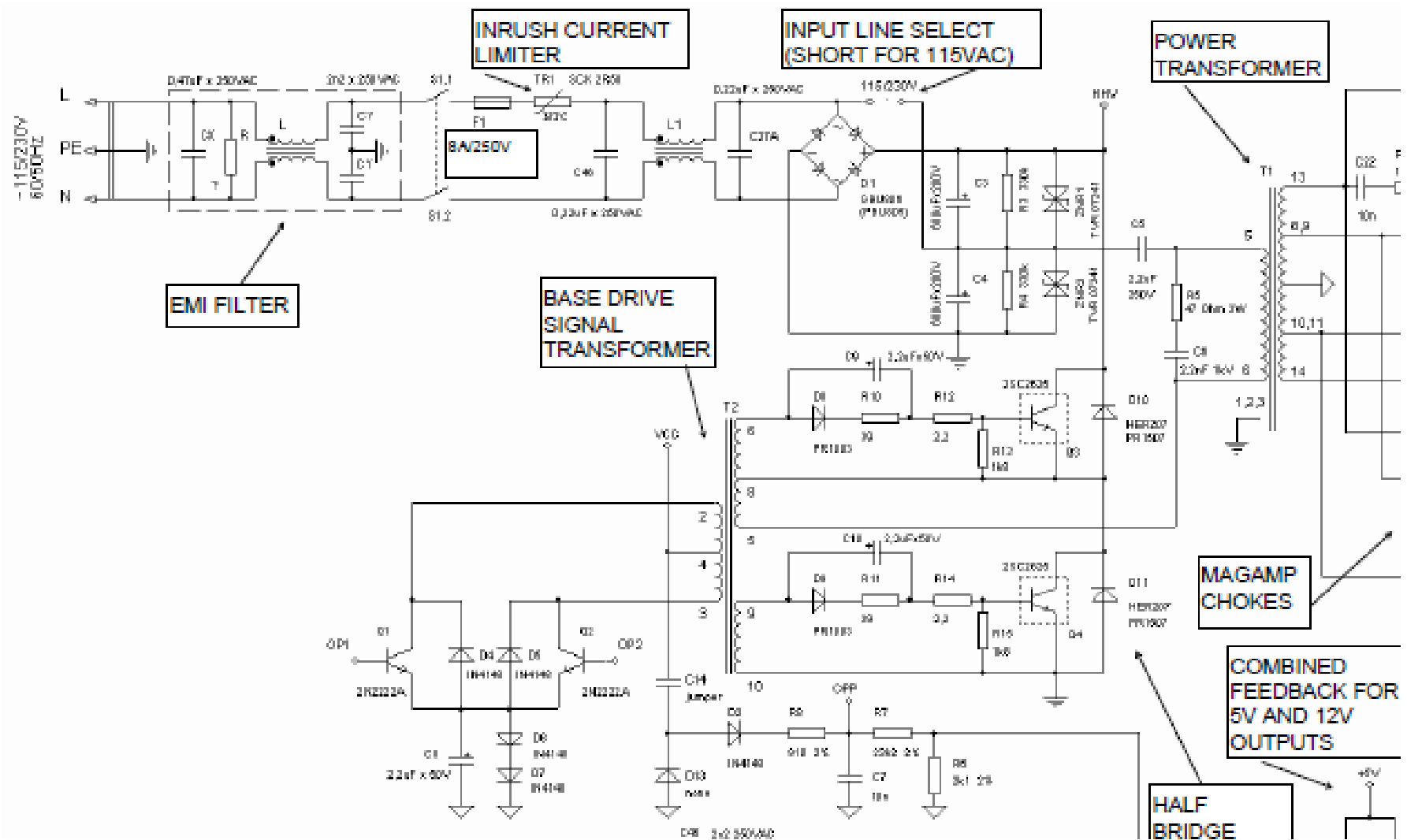


PUNOTALSNI ISPRAVLJAČ U GRECOVOM SPOJU: SIMULACIJA

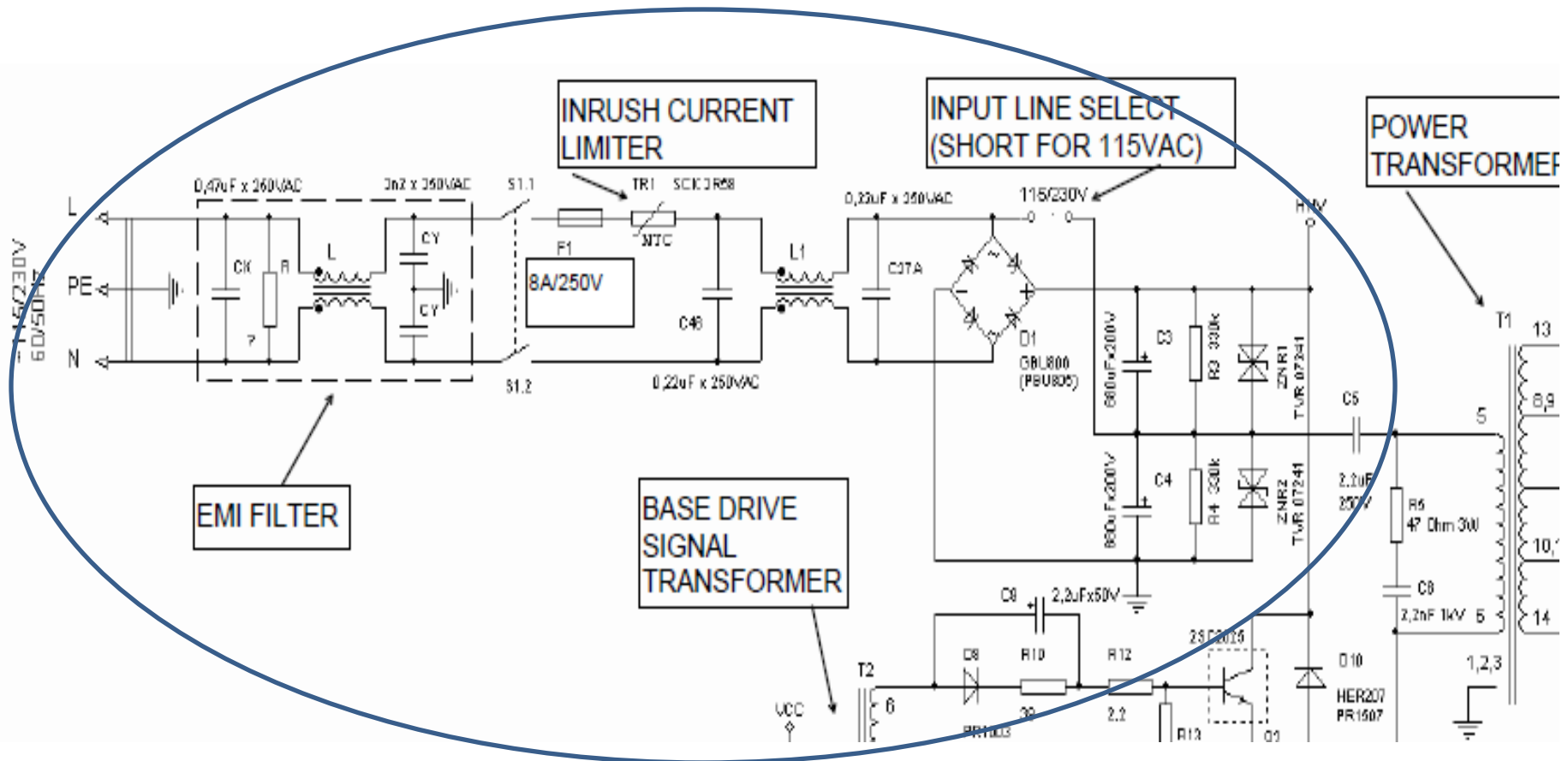
DETALJAN PRIKAZ IZLAZNOG NAPONA PRI 230V, 50Hz i 115V,50Hz



ELEKTRIČNA ŠEMA TIPIČNOG ATX-napajanja

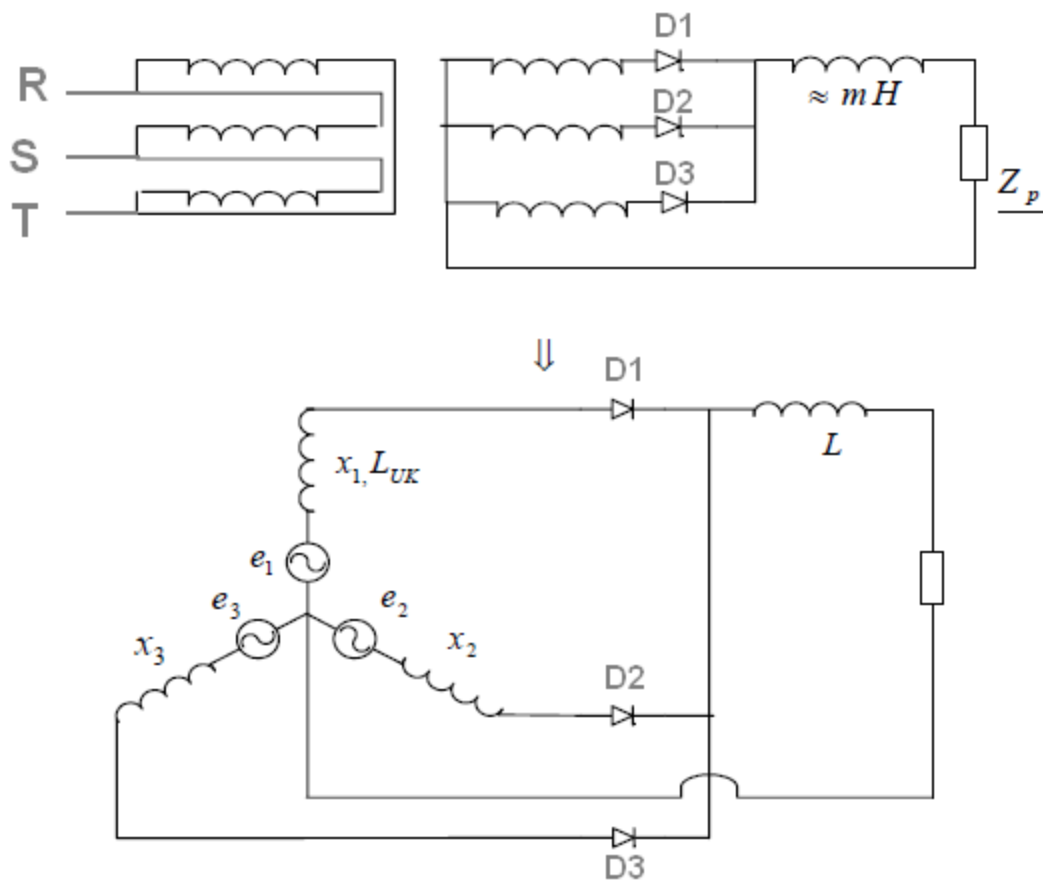


ATX napajanje-DETALJ ULAZNOG ISPRAVLJAČA

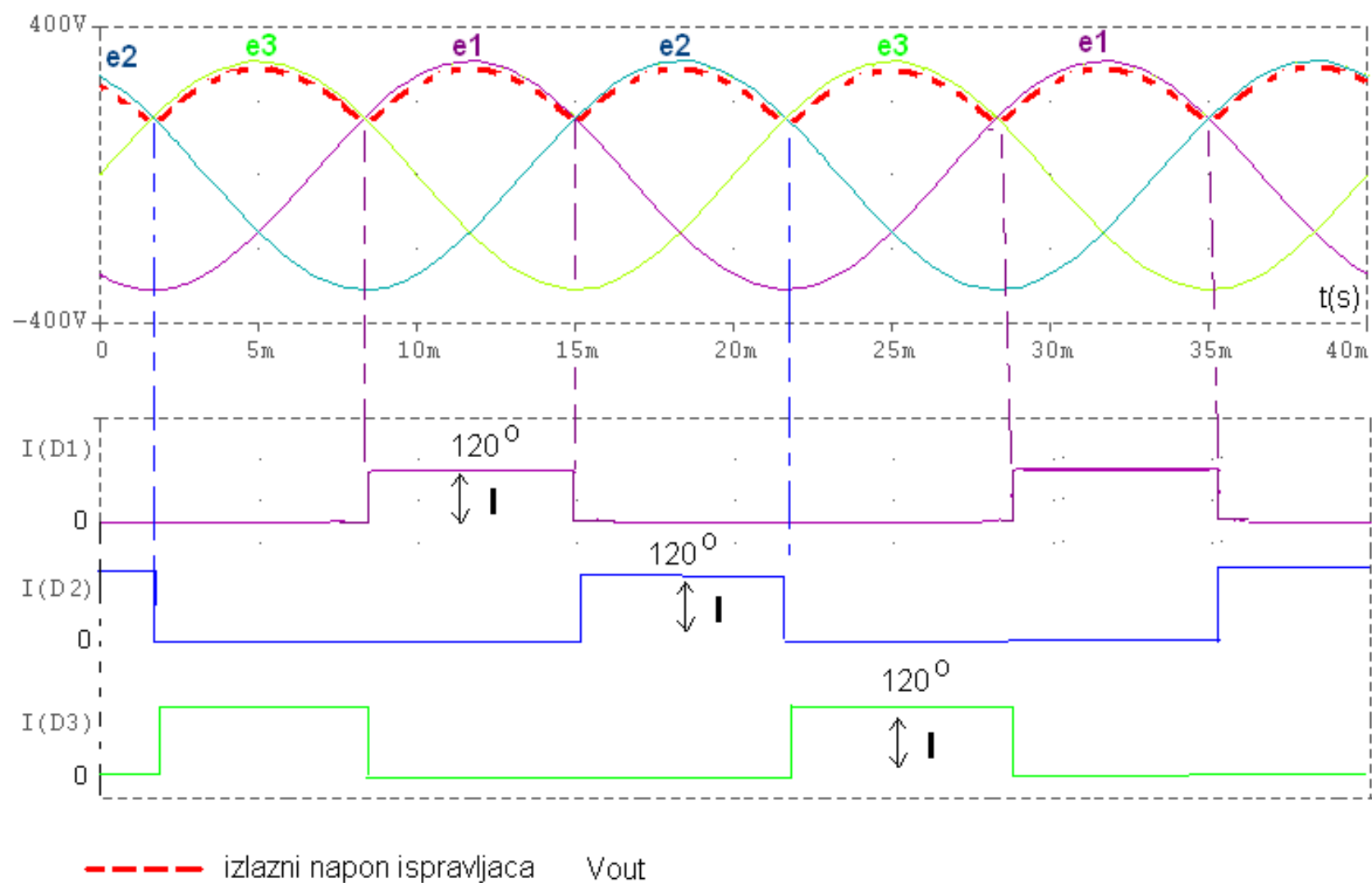


TROFAZNI AC-DC pretvarači (MREŽOM VOĐENI ISPRAVLJAČI)

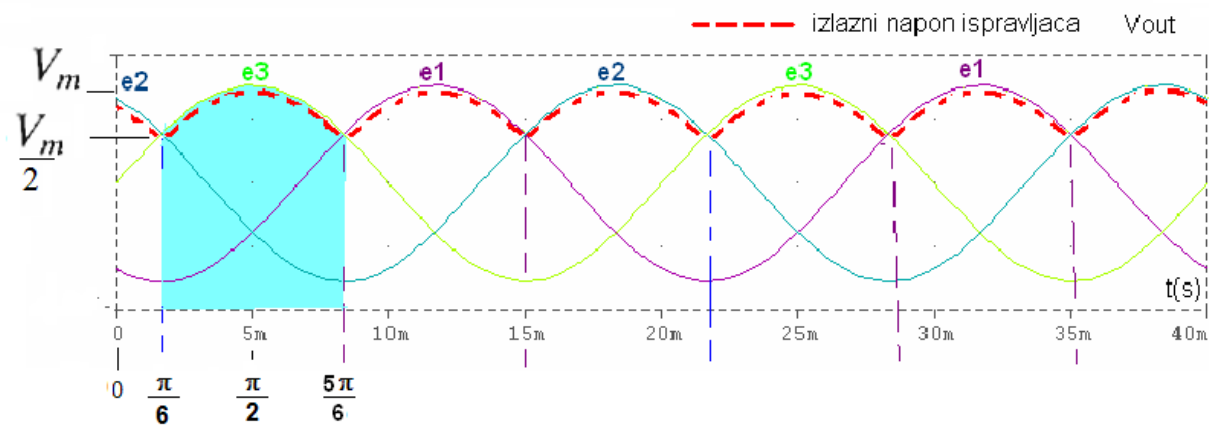
Trofazni ispravljač sa transformatorom sa srednjom tačkom



TROFAZNI ISPRAVLJAČ SA TRANSFORMATOROM SA SREDNJOJ TAČKOM- talasni oblici



TROFAZNI ISPRAVLJAČ SA TRANSFORMATOROM SA SREDNJOJ TAČKOM- proračuni



SREDNJA VREDNOST IZLAZNOG NAPONA

$$V_{dc} = \frac{2}{2\pi/3} \int_0^{\pi/3} V_m \cos \omega t d(\omega t) = V_m \frac{3}{\pi} \sin \frac{\pi}{3}$$

$$V_{dc} = 0.827 V_m$$

TALASNOST

$$\Delta V = V_m - \frac{V_m}{2}$$

$$\Delta V = 0.5 V_m$$

EFEKTIVNA VREDNOST IZLAZNOG NAPONA

$$V_{rms} = \left[\frac{2}{2\pi/3} \int_0^{\pi/3} V_m^2 \cos^2 \omega t d(\omega t) \right]^{1/2}$$

$$V_{rms} = V_m \left[\frac{3}{2\pi} \left(\frac{\pi}{3} + \frac{1}{2} \sin \frac{2\pi}{3} \right) \right]^{1/2}$$

$$V_{rms} = 0.5945 V_m$$

EFEKTIVNA VREDNOST STRUJE DIODE (SEKUNDARNE STRUJE TRANSFORMATORA)

$$I_m = V_m / R$$

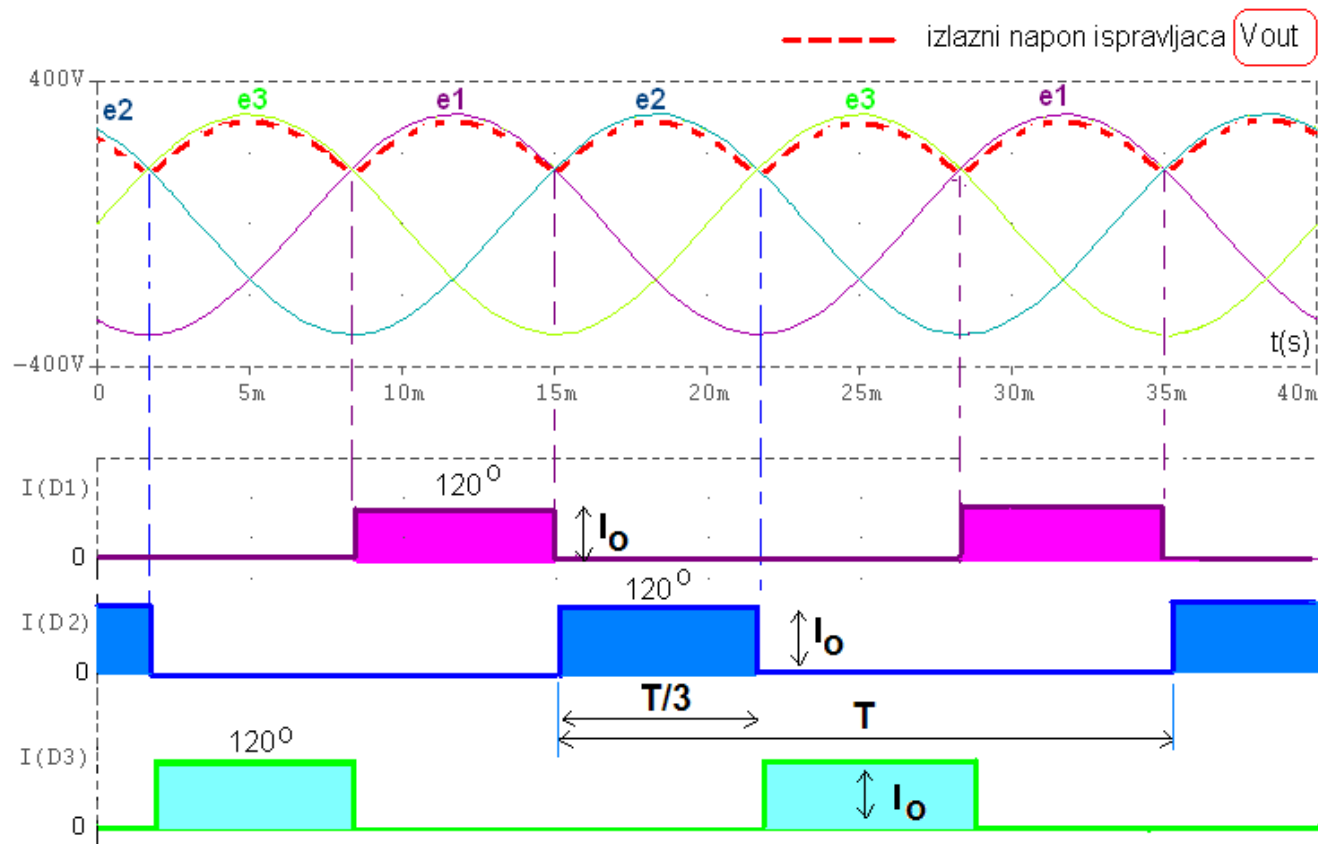
$$I_s = \left[\frac{2}{2\pi} \int_0^{\pi/3} I_m^2 \cos^2 \omega t d(\omega t) \right]^{1/2}$$

$$I_s = I_m \left[\frac{1}{2\pi} \left(\frac{\pi}{3} + \frac{1}{2} \sin \frac{2\pi}{3} \right) \right]^{1/2} = \frac{V_{rms}}{R}$$

OTPORNO OPTEREĆENJE!!!!

ŠTA KAD JE OPTEREĆENJE STRUJNI PONOR???

TROFAZNI ISPRAVLJAČ SA TRANSFORMATOROM SA SREDNJOM TAČKOM- proračuni kad je opterećenje strujni ponor



**SREDNJA VREDNOST STRUJE DIODE
(SEKUNDARA TRANSFORMATORA)**

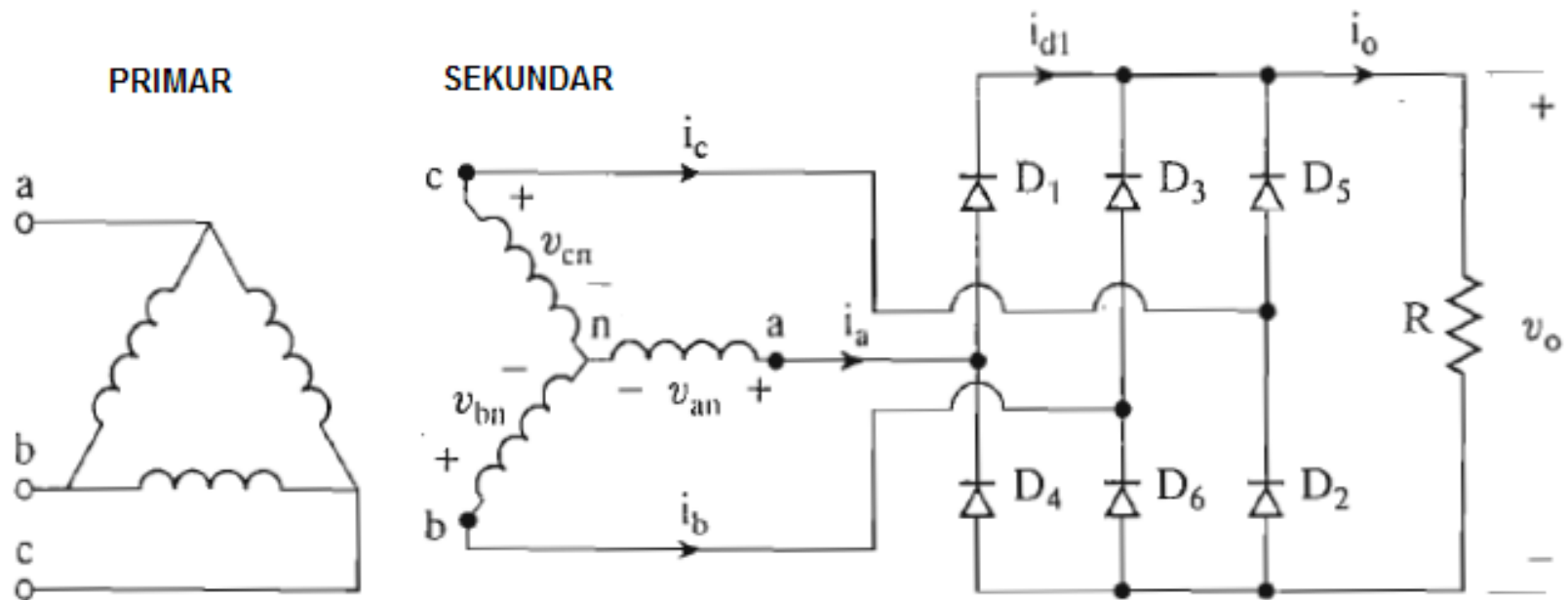
$$I_{avg} = \frac{1}{T} \int_0^T i(t) dt = I_o \frac{T/3}{T} = \frac{I_o}{3}$$

**EFEKTIVNA VREDNOST STRUJE DIODE
(SEKUNDARA TRANSFORMATORA)**

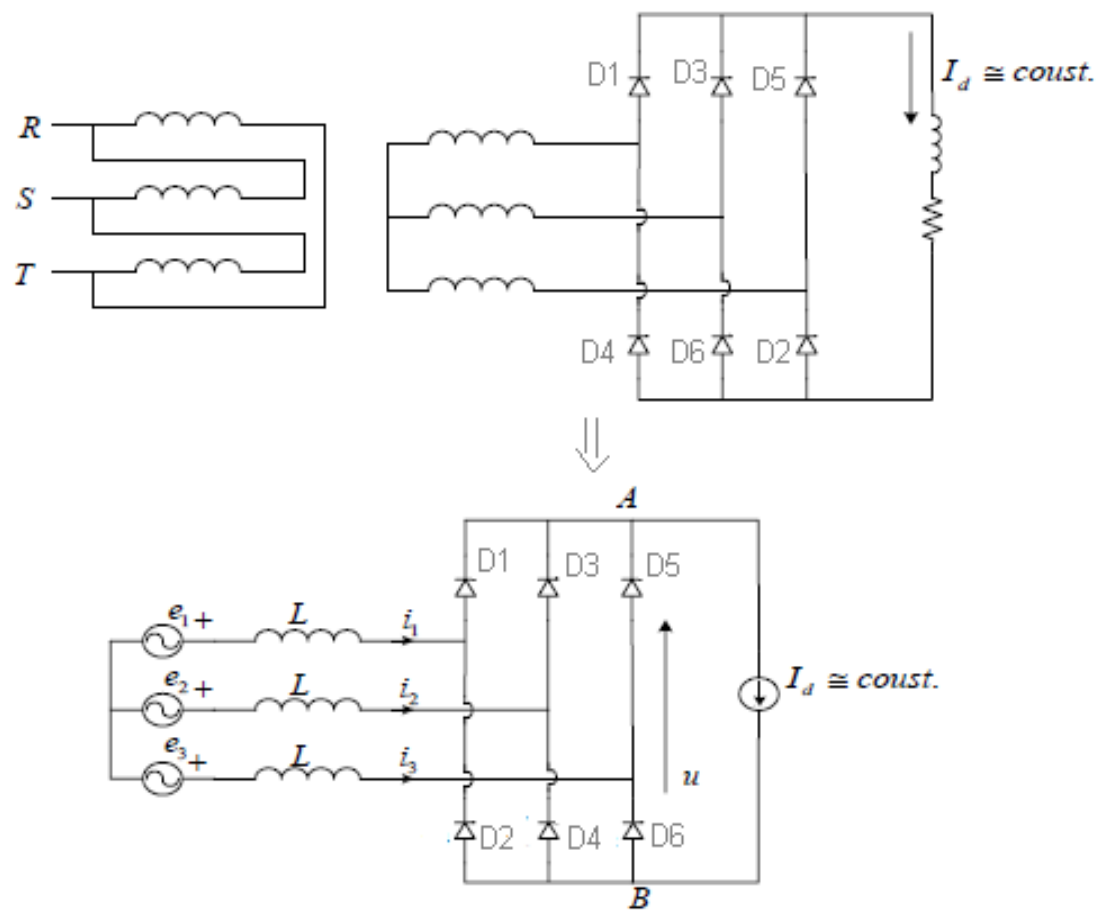
$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt} = \sqrt{I_o^2 \frac{T/3}{T}} = \frac{I_o}{\sqrt{3}}$$

TROFAZNI MOSNI ISPRAVLJAČ-otporno opterećenje

$$v_{an} = V_m \sin(\omega t) \quad v_{bn} = V_m \sin(\omega t - 120^\circ) \quad v_{cn} = V_m \sin(\omega t - 240^\circ)$$

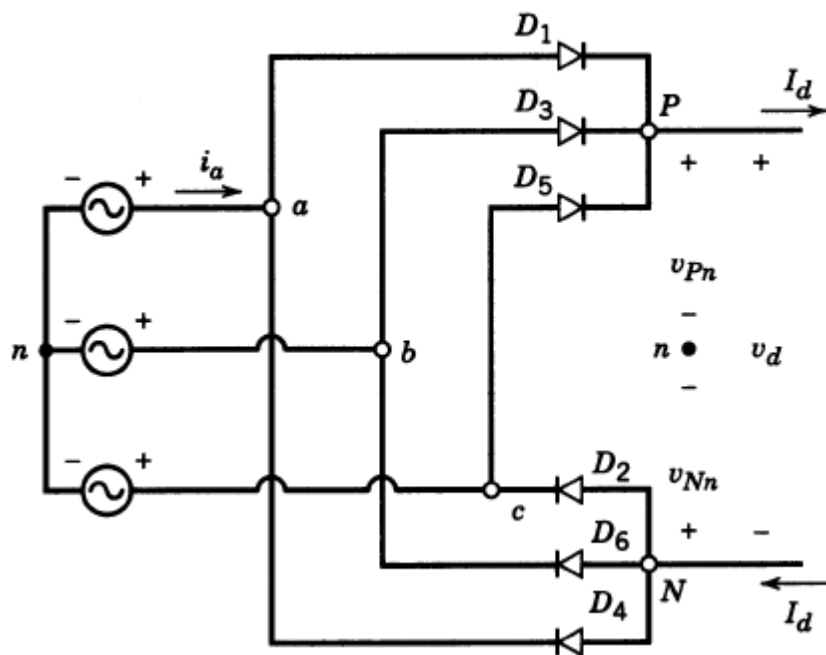
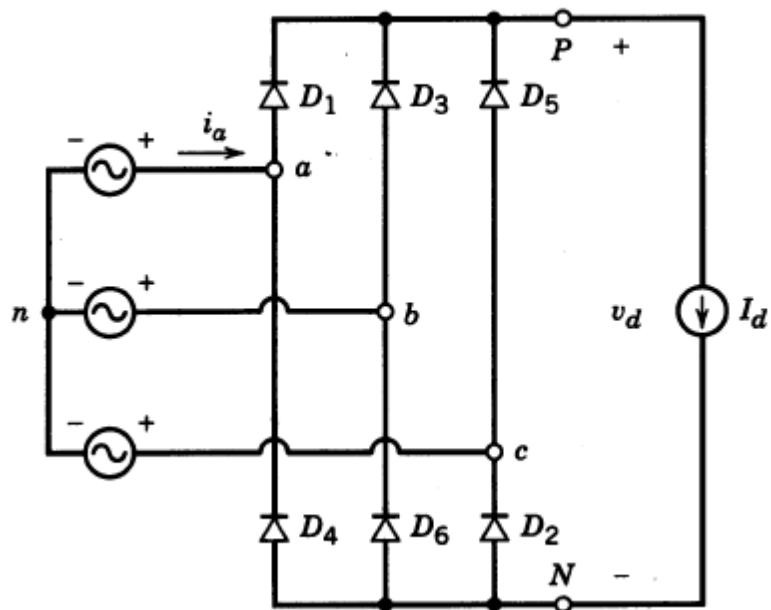


TROFAZNI MOSNI ISPRAVLJAČ-opterećenje strujni ponor I_d

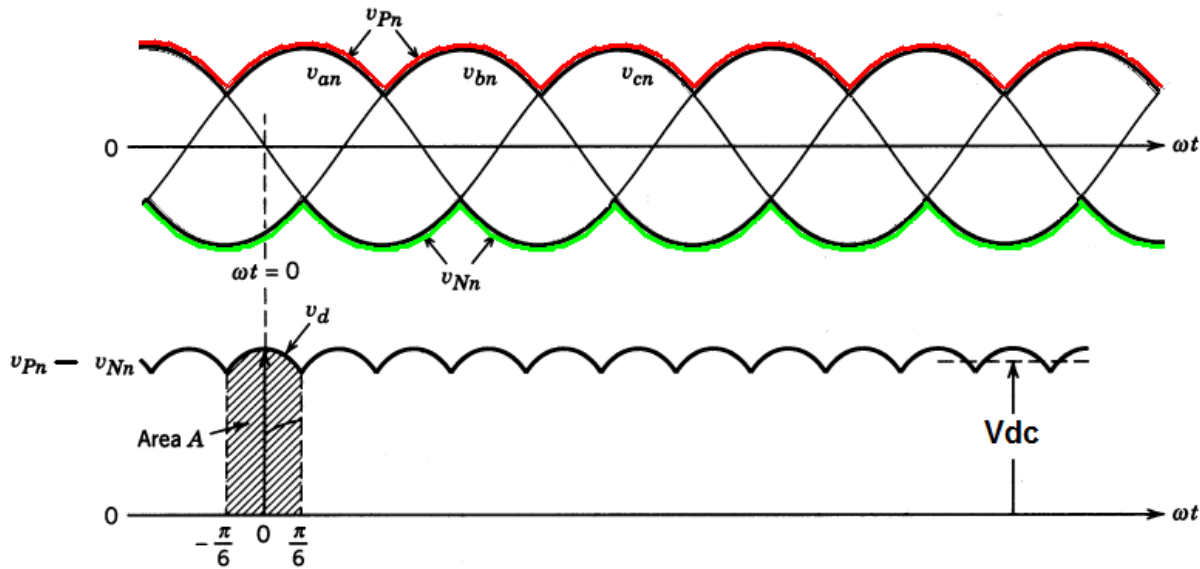


TROFAZNI MOSNI ISPRAVLJAČ

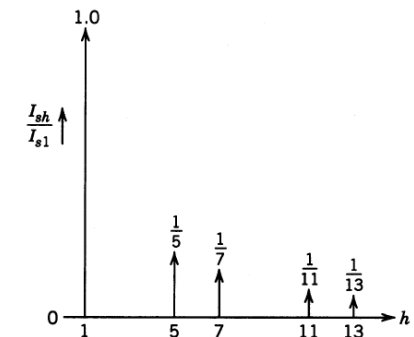
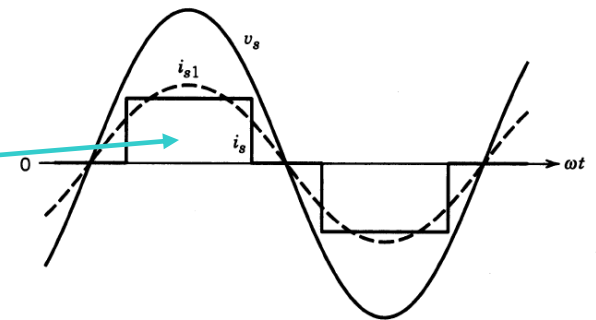
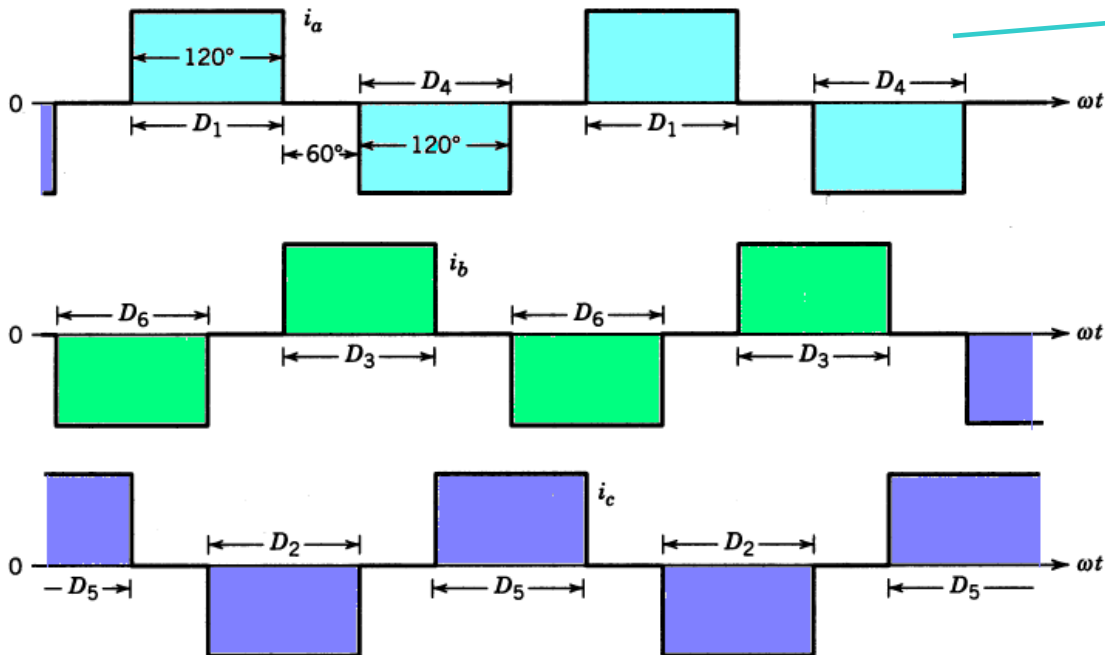
EKVIVALENCIJA SA DVA TROFAZNA POLUMOSNA ISPRAVLJAČA



TROFAZNI MOSNI ISPRAVLJAČ-talasni oblici

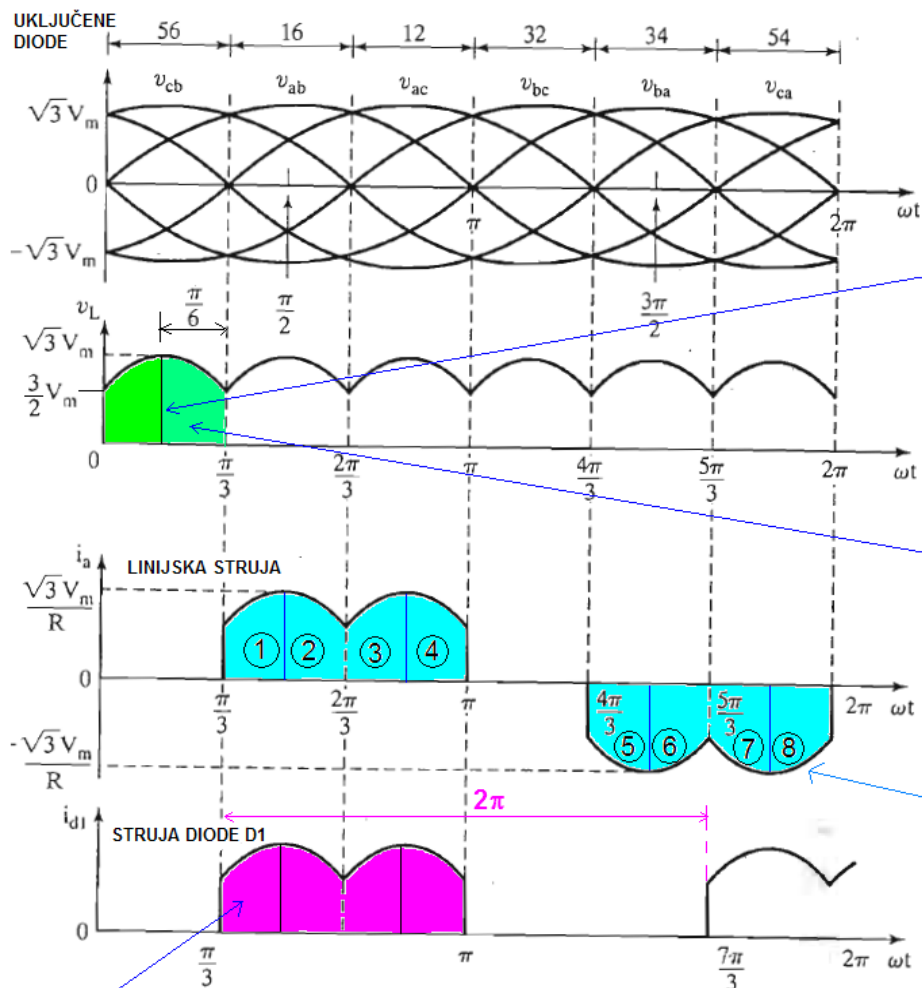


LINIJSKI NAPON I
LINIJSKA STRUJA



HARMONIJSKI SASTAV

TROFAZNI MOSNI ISPRAVLJAČ- izračunavanje srednjih i efektivnih vrednosti



$$v_{ab} = \sqrt{3} V_m \sin(\omega t + 30^\circ) \quad v_{bc} = \sqrt{3} V_m \sin(\omega t - 90^\circ)$$

$$v_{ca} = \sqrt{3} V_m \sin(\omega t - 210^\circ)$$

SREDNJA VREDNOST NAPONA NA OPTEREĆENJU (IZLAZNI NAPON)

$$V_{dc} = \frac{2}{2\pi/6} \int_0^{\pi/6} \sqrt{3} V_m \cos \omega t d(\omega t)$$

TALASNOST

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_m = 1.654V_m$$

$$\Delta V = \sqrt{3}V_m - \frac{3}{2}V_m = 0.23V_m$$

EFEKTIVNA VREDNOST NAPONA NA OPTEREĆENJU (IZLAZNI NAPON)

$$V_{rms} = \left[\frac{2}{2\pi/6} \int_0^{\pi/6} 3V_m^2 \cos^2 \omega t d(\omega t) \right]^{1/2}$$

$$V_{rms} = \left(\frac{3}{2} + \frac{9\sqrt{3}}{4\pi} \right)^{1/2} V_m = 1.6554V_m$$

EFEKTIVNA VREDNOST LINIJSKE STRUJE

$$I_s = \left[\frac{8}{2\pi} \int_0^{\pi/6} I_m^2 \cos^2 \omega t d(\omega t) \right]^{1/2}$$

$$= I_m \left[\frac{2}{\pi} \left(\frac{\pi}{6} + \frac{1}{2} \sin \frac{2\pi}{6} \right) \right]^{1/2}$$

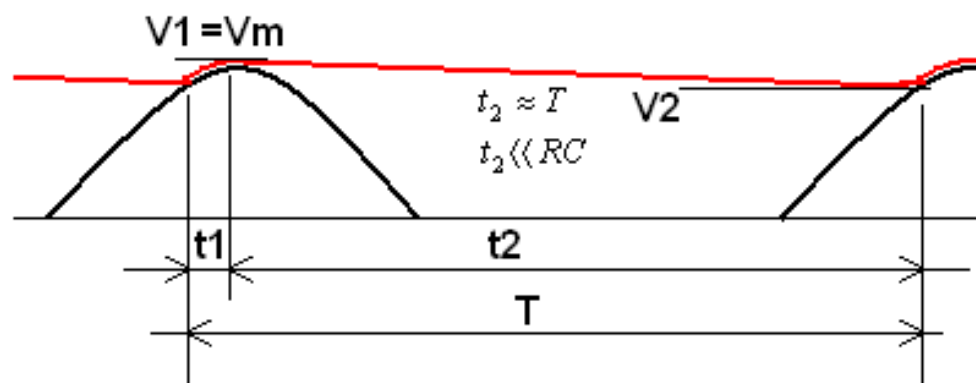
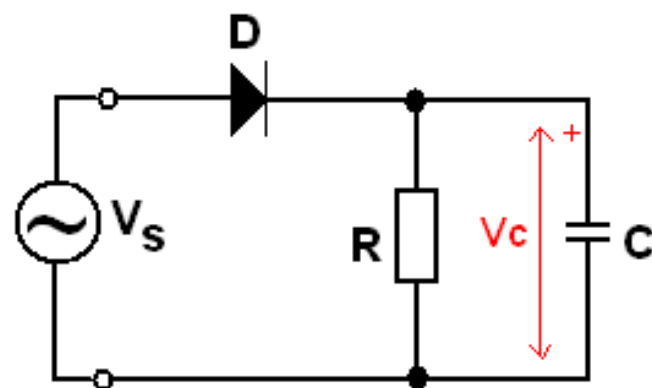
$$I_s = 0.7804I_m$$

$$I_m = V_m/R$$

SREDNJA VREDNOST STRUJE DIODE

$$I_d = \frac{4}{2\pi} \int_0^{\pi/6} I_m \cos \omega t d(\omega t) = I_m \frac{2}{\pi} \sin \frac{\pi}{6} = 0.3183I_m$$

MONOFAZNI ISPRAVLJAČI (IZBOR KAPACITIVNOG FILTRA) -rekapitulacija

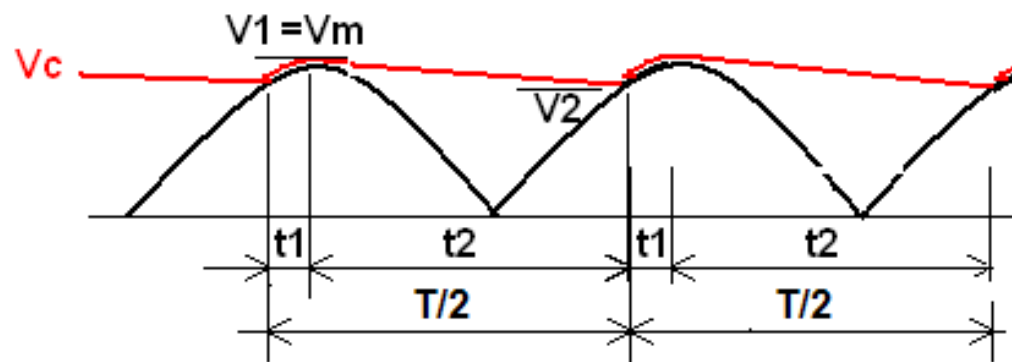
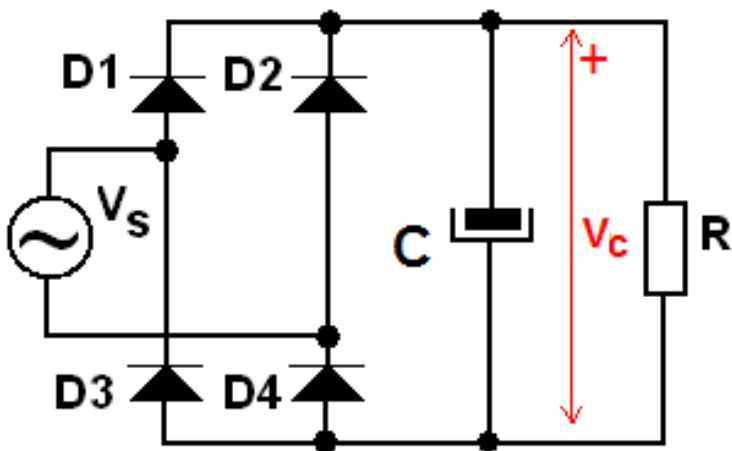


$$\Delta V = V_m \cdot \frac{t_2}{RC} = V_m \cdot \frac{T}{RC} = V_m \cdot \frac{1}{fRC}$$

$$t_2 \approx T$$

$$V_{DC} = V_m - \frac{\Delta V}{2} = V_m - \frac{V_m}{2fRC} = V_m \cdot \frac{2fRC - 1}{2fRC}$$

$$\frac{\Delta V}{V_{DC}} = 2 \cdot \frac{1}{2fRC - 1}$$



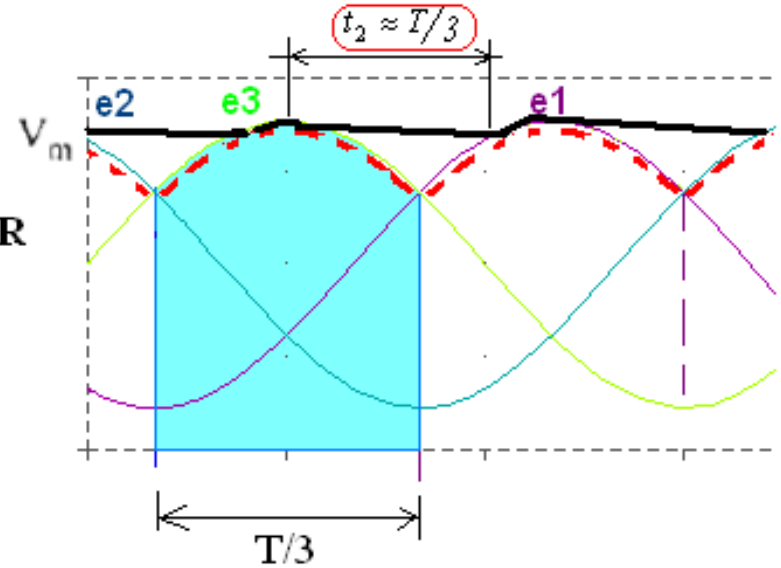
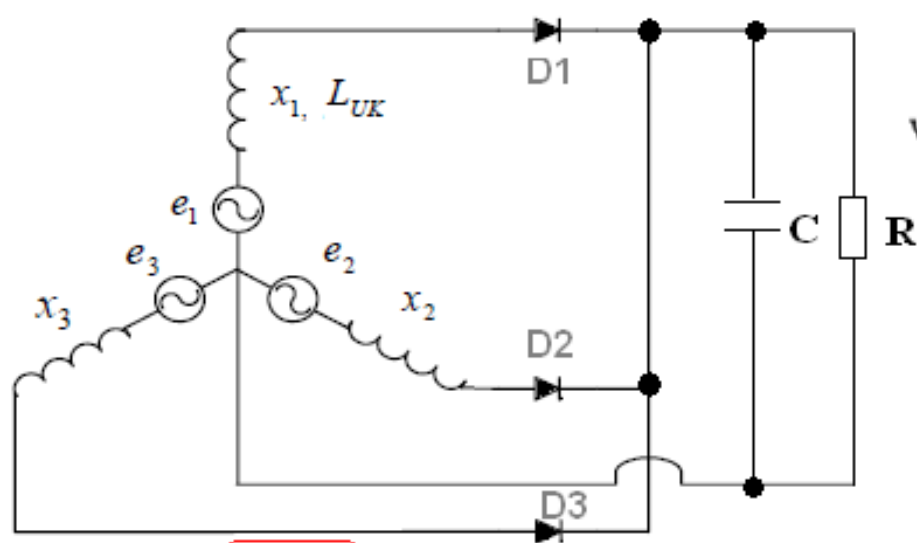
$$\Delta V = V_m \cdot \frac{t_2}{RC} \approx V_m \cdot \frac{T}{2RC} = V_m \cdot \frac{1}{2fRC}$$

$$t_2 = \frac{T}{2}$$

$$V_{DC} = V_m - \frac{\Delta V}{2} = V_m - \frac{V_m}{4fRC} = V_m \cdot \frac{4fRC - 1}{4fRC}$$

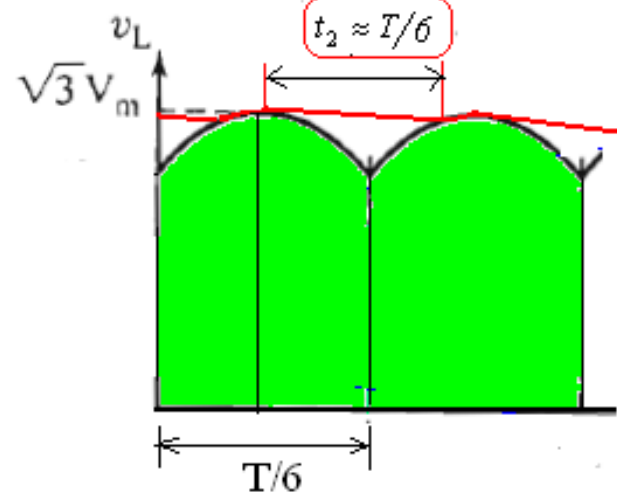
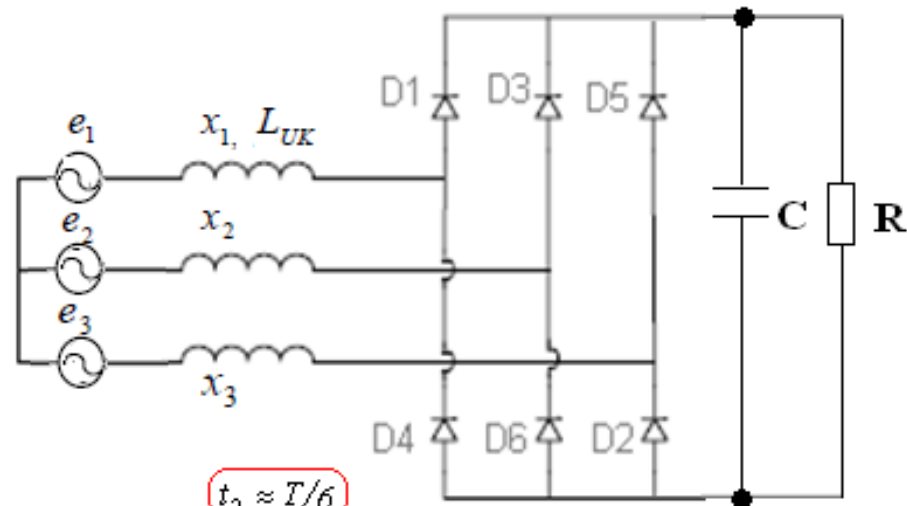
$$\frac{\Delta V}{V_{DC}} = 2 \cdot \frac{1}{4fRC - 1}$$

TROFAZNI ISPRAVLJAČI (IZBOR KAPACITIVNOG FILTRA) - rekapitulacija



$$\Delta V = V_m \cdot \frac{t_2}{RC} = V_m \cdot \frac{T}{3RC} = V_m \cdot \frac{1}{3fRC}$$

$$V_{DC} = V_m - \frac{\Delta V}{2} = V_m - \frac{V_m}{6fRC} = V_m \cdot \frac{6fRC - 1}{6fRC} \quad \frac{\Delta V}{V_{DC}} = 2 \cdot \frac{1}{6fRC - 1}$$



$$\Delta V = V_m \cdot \frac{t_2}{RC} = V_m \cdot \frac{T}{6RC} = V_m \cdot \frac{1}{6fRC}$$

$$V_{DC} = V_m - \frac{\Delta V}{2} = V_m - \frac{V_m}{12fRC} = V_m \cdot \frac{12fRC - 1}{12fRC} \quad \frac{\Delta V}{V_{DC}} = 2 \cdot \frac{1}{12fRC - 1}$$