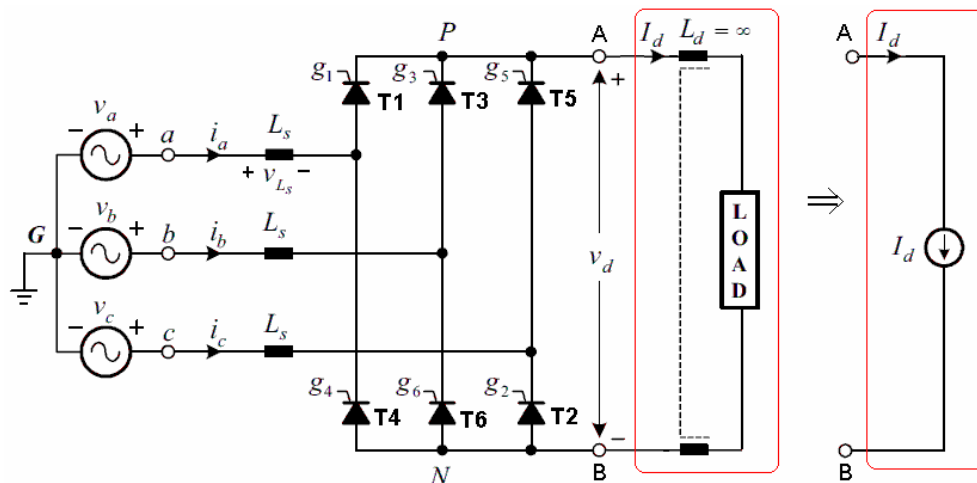


AC/DC ENERGETSKI PRETVARAČI (KONTROLISANI TIRISTORSKI ISPRAVLJAČI)



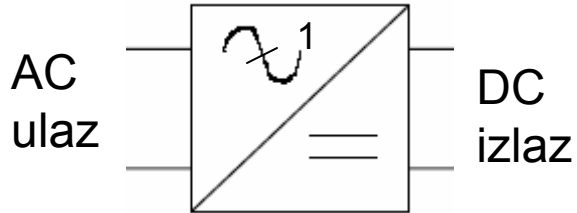
Predavač: Prof. dr Željko Despotović

AC/DC pretvarači-OPŠTE

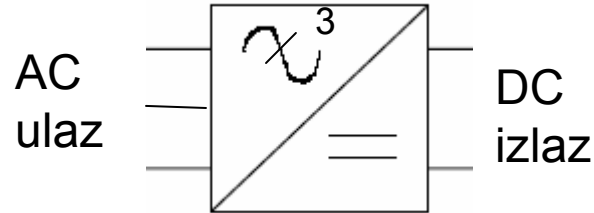
AC ulaz: monofazni ili trofazni

220V, 50/60Hz

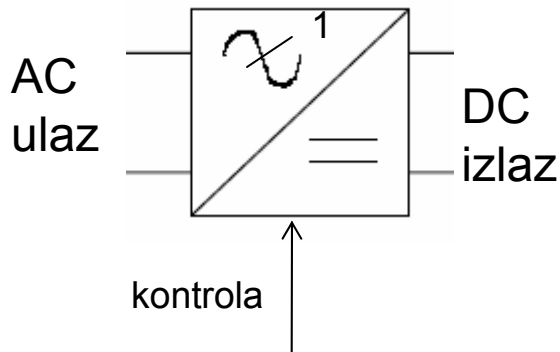
3x380/220V, 50/60Hz



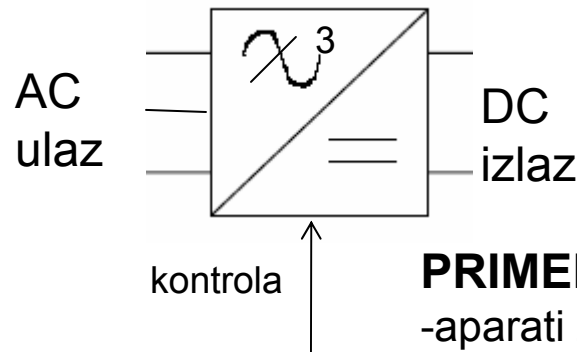
MONOFAZNI DIODNI ISPRAVLJAČI



TROFAZNI DIODNI ISPRAVLJAČI



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

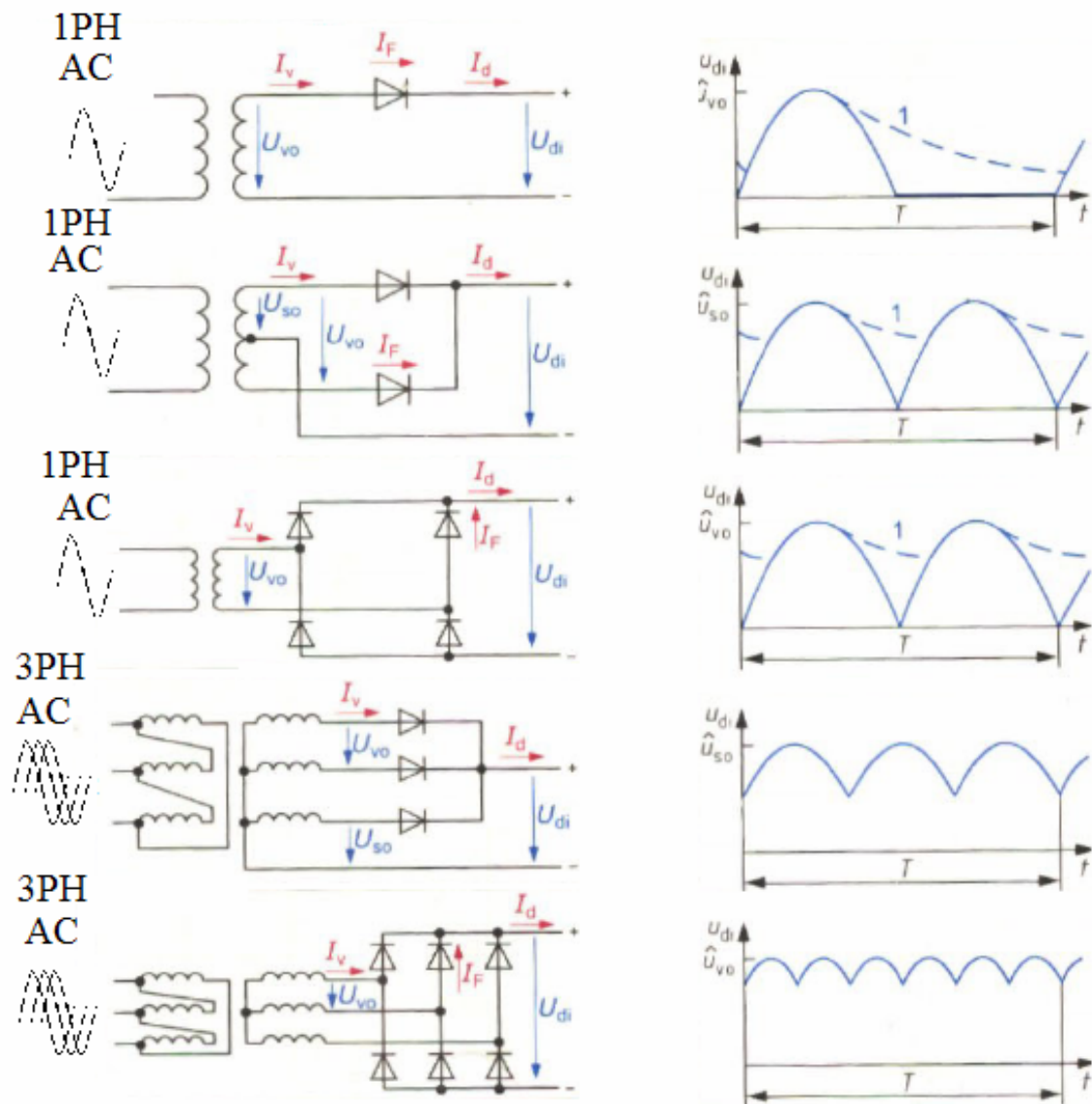


PRIMENA:

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

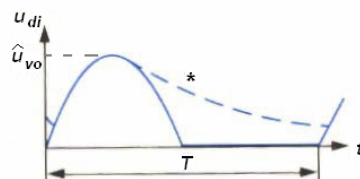
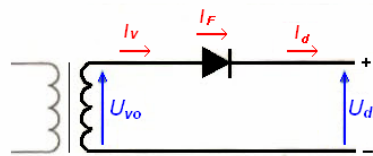
TIRISTORSKI: POLUUPRAVLJIVI I PUNOUPRAVLJIVI

NEUPRAVLJIVI AC/DC PRETVARAČI DIODNI ISPRAVLJAČI (rekapitulacija)

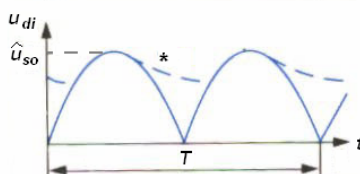
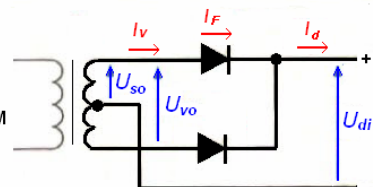


NEUPRAVLJIVI PRETVARAČI (ISPRAVLJAČI)

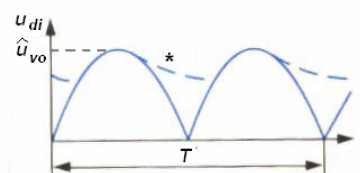
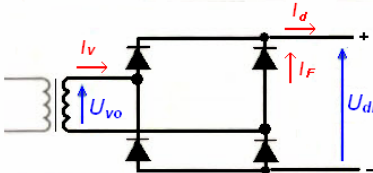
JEDNOIMPULSNI
SPOJ BEZ
IZVEDENE
SREDJE TAČKE
M1U



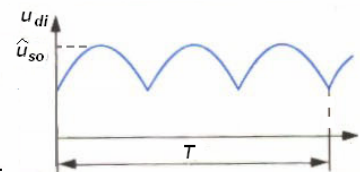
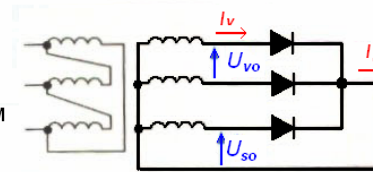
DVOIMPULSNI SPOJ
SA IZVEDENOM
SREDNJOM TAČKOM
M2U



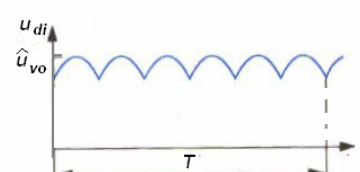
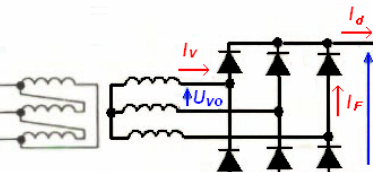
DVOIMPULSNI
MOSNI SPOJ
B2U



TROIMPULSNI SPOJ
SA IZVEDENOM
SREDNJOM TAČKOM
M3U



ŠESTOIMPULSNI
MOSNI SPOJ
B6U



p - BROJ IMPULSA

U_{vo} - EFEKTIVNA VREDNOST LINIJSKOG NAPONA

$\hat{U}_{vo}$ - MAKSIMALNA VREDNOST LINIJSKOG NAPONA

U_{di} - SREDNJA VREDNOST IZLAZNOG NAPONA

U_{im} - IDEALNI MAKSIMALNI INVERZNI NAPON

U_{iRMS} - EFEKTIVNA VREDNOST IZLAZNOG NAPONA

I_d - JEDNOSMERNNA VREDNOST IZLAZNE STRUJE

I_{FAV} - SREDNJA VREDNOST STRUJE DIODE

I_{FRMS} - EFEKTIVNA VREDNOST STRUJE DIODE

S_{Li} - TIPSKA SNAGA TRANSFORMATORA

W_u - FAKTOR TALASNOSTI

$$U_{iRMS}^2 = U_{di}^2 + U_{ac}^2$$

$$W_u = \frac{U_{ac}}{U_{di}}$$

$$W_u = \sqrt{\left(\frac{U_{iRMS}}{U_{di}}\right)^2 - 1}$$

TUF - FAKTOR ISKORIŠĆENJA TRANSFORMATORA

$$TUF = \left(\frac{S_{Li}}{U_{di} \cdot I_d}\right)^{-1}$$

KARAKTERISTIČNE VELIČINE SPOJEVA

p	$\frac{U_{di}}{U_{vo}}$	$\frac{U_{im}}{U_{di}}$	$\frac{I_v}{I_d}$	$\frac{I_{FAV}}{I_d}$	$\frac{I_{FRMS}}{I_d}$	$\frac{S_{Li}}{U_{di} \cdot I_d}$	W_u
1	$\frac{\sqrt{2}}{\pi}$ 0.45	π (3.14)	$\frac{\pi}{2}$ (1.57)	1.0	$\frac{\pi}{2}$ (1.57)	$\frac{\pi^2}{2\sqrt{2}}$ (3.49)	1.21
		$2\pi^{**}$ 6.28					
2	$\frac{\sqrt{2}}{\pi}$ 0.45	π (3.14)	$\frac{\pi}{4}$ (0.785)	$\frac{1}{2}$ (0.50)	$\frac{\pi}{4}$ (0.785)	$\frac{\pi^2}{8}$ (1.23)	0.48
		π^{**} 3.14**					
2	$\frac{2\sqrt{2}}{\pi}$ (0.90)	$\frac{\pi}{2}$ (1.57)	$\frac{\pi}{2\sqrt{2}}$ (1.11)	$\frac{1}{2}$ (0.50)	$\frac{\pi}{4}$ (0.785)	$\frac{\pi^2}{8}$ (1.23)	0.48
		$\frac{\pi}{2}^{**}$ 1.57**	1.00***				
3	$\frac{3\sqrt{2}}{2\pi}$ (0.675)	$\frac{2\pi}{3}$ (2.09)	0.588	$\frac{1}{3}$ (0.333)	0.588	$\frac{\pi^2}{8}$ (1.23)	0.18
			$\frac{\sqrt{3}}{3}^{***}$ 0.577***		$\frac{\sqrt{3}}{3}^{***}$ 0.577***		
6	$\frac{3\sqrt{2}}{\pi}$ 1.35	$\frac{\pi}{3}$ (1.05)	$\frac{3\sqrt{3}}{2\pi}$ (0.820)	$\frac{1}{3}$ (0.333)	0.580	1.06	0.04
			$\frac{\sqrt{2}}{\sqrt{3}}^{***}$ 0.816***		$\frac{\sqrt{3}}{3}^{***}$ 0.577***	$\frac{\pi}{3}^{***}$ 1.05***	

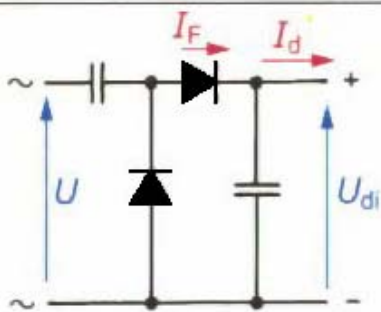
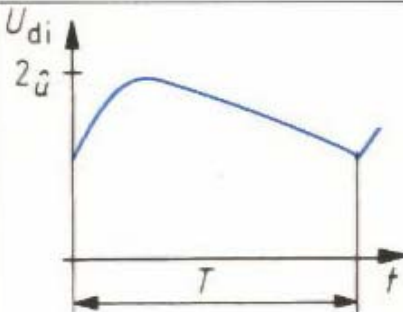
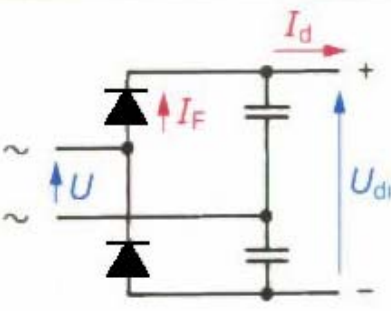
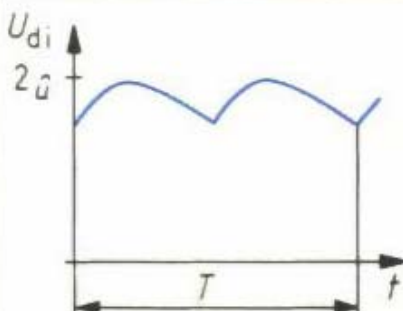
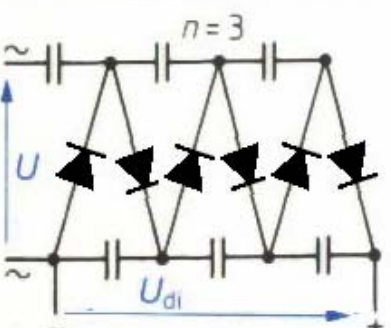
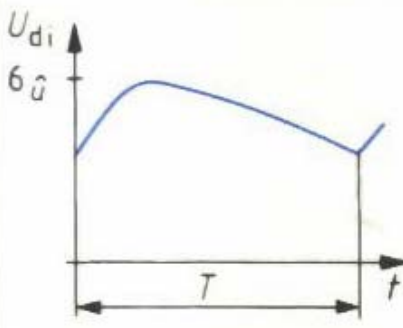
NAPOMENA:

* NAPONSKA KARAKTERISTIKA SA KONDENZATOROM ZA FILTRIRANJE

** MAKSIMALNE VREDNOSTI SA KONDENZATOROM ZA FILTRIRANJE

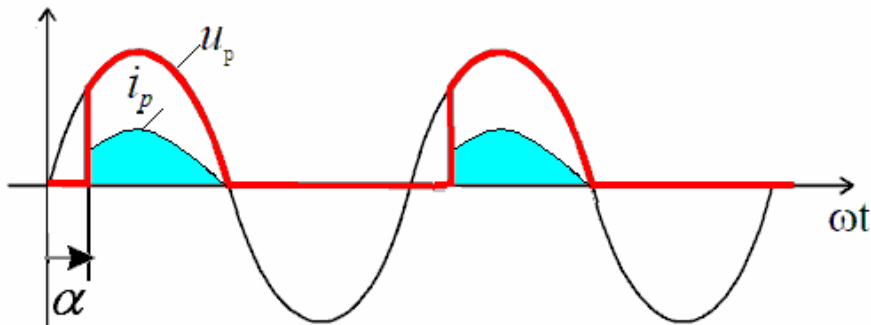
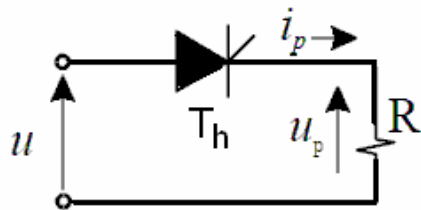
*** KARAKTERISTIČNE VREDNOSTI SA INDUKTIVNIM OPTEREĆENJEM

NEUPRAVLJIVI AC/DC PRETVARAČI -DIODNI UMNOŽAVAČI (rekapitulacija)

Nazivi	Spoj	Naponska karakteristika	Karakteristične vrednosti sklopova			
			$\frac{U_{di}}{U}$	$\frac{\hat{u}_R}{U}$	$\frac{I_{FAV}}{I_d}$	$\frac{f_{\hat{u}}}{f}$
Jedno-impulsni udvostručivač D1			2,82	2,82	1,0	1
Dvo-impulsni udvostručivač D2			2,82	2,82	0,5	2
Jedno-impulsni umnogostručivač V1			$n \cdot 2 \cdot \sqrt{2}$ za $n=3$ 8,48	2,82	n za 2. ste- pen 2	1

MONOFAZNI POLUTALASNI KONTROLISANI ISPRAVLJAČI

sa otpornim opterećenjem



Srednja vrednost izlaznog napona

$$U_{PAV} = \frac{1}{T} \int_0^T u_p dt = \frac{\omega}{2\pi} \int_{\alpha/\omega}^{\pi/\omega} U\sqrt{2} \sin \omega t dt = \frac{U\sqrt{2}}{2\pi} \int_{\alpha}^{\pi} \sin \omega t d(\omega t)$$

$$U_{PAV} = \frac{U\sqrt{2}}{2\pi} (1 + \cos \alpha)$$

Srednja izlazne struje

$$I_{PAV} = \frac{1}{T} \int_0^T i_p dt = \frac{1}{T} \int_0^T \frac{u_p}{R} dt = \frac{U_{PAV}}{R} = \frac{U}{\pi R} \frac{\sqrt{2}}{2} (1 + \cos \alpha)$$

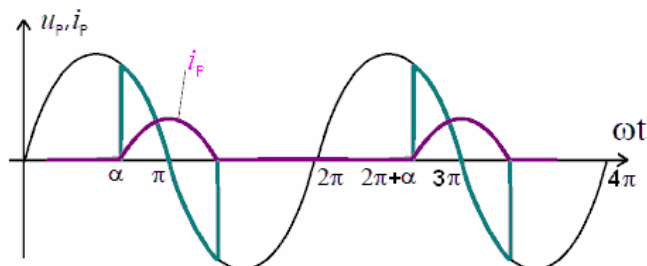
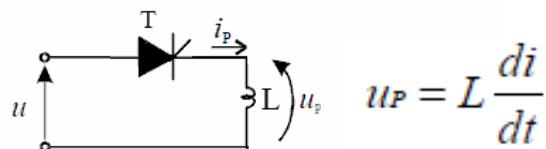
Efektivna vrednost izlaznog napona

$$U_{PRMS} = \sqrt{\frac{1}{T} \int_0^T u_p^2 dt} = \sqrt{\frac{\omega}{2\pi} \int_{\alpha/\omega}^{\pi/\omega} 2U^2 \sin^2 \omega t dt}$$

$$U_{PRMS} = \frac{U}{\sqrt{2}} \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \sin 2\alpha}$$

MONOFAZNI KONTROLISANI ISPRAVLJAČI

POLUTALASNI sa čisto induktivnim opterećenjem



Struja potrošača

$$i_P = \frac{1}{L} \int_0^t u_P dt = \frac{1}{L} \int_{\alpha/\omega}^t U\sqrt{2} \sin \omega t dt = \frac{U\sqrt{2}}{\omega L} (\cos \alpha - \cos \omega t)$$

Srednja vrednost struje potrošača

$$\begin{aligned} I_{PAV} &= \frac{1}{T} \int_0^T i_P dt = \frac{\omega}{2\pi} \int_{\alpha/\omega}^{(2\pi-\alpha)/\omega} \frac{U\sqrt{2}}{\omega L} (\cos \alpha - \cos \omega t) dt \Rightarrow \\ \Rightarrow I_{PAV} &= \frac{\omega}{2\pi} \frac{U\sqrt{2}}{\omega L} \left[\left(\frac{2\pi-\alpha}{\omega} - \frac{\alpha}{\omega} \right) \cos \alpha - \frac{1}{\omega} \sin \omega t \Big|_{\alpha}^{2\pi-\alpha} \right] \Rightarrow \\ \Rightarrow I_{PAV} &= \frac{U\sqrt{2}}{\omega L} \left[\left(1 - \frac{\alpha}{\pi} \right) \cos \alpha + \frac{1}{\pi} \sin \alpha \right] \end{aligned}$$

Za $\alpha=0$ je:

$$I_{PAV} = \frac{U\sqrt{2}}{\omega L}$$

Opseg upravljanja $0 < \alpha < 180^\circ$

$$U_{PAV} = 0$$

Efektivna vrednost napona potrošača

$$\begin{aligned} U_{PRMS} &= \sqrt{\frac{1}{T} \int_0^T u_P^2 dt} = \sqrt{\frac{\omega}{2\pi} \int_{\alpha/\omega}^{(2\pi-\alpha)/\omega} 2U^2 \sin^2 \omega t dt} \Rightarrow \\ U_{PRMS} &= U \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \sin 2\alpha} \end{aligned}$$

$$\begin{aligned} I_{PRMS} &= \sqrt{\frac{1}{T} \int_0^T i_P^2 dt} = \sqrt{\frac{\omega}{2\pi} \int_{\alpha/\omega}^{(2\pi-\alpha)/\omega} \left[\frac{U\sqrt{2}}{\omega L} (\cos \alpha - \cos \omega t) \right]^2 dt} \Rightarrow \\ I_{PRMS} &= \frac{U}{\omega L} \sqrt{\frac{1}{2\pi} [(2 + 2 \cos 2\alpha)(2\pi - 2\alpha) + 3 \sin 2\alpha]} \end{aligned}$$

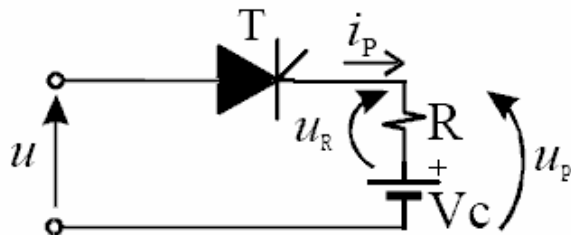
Za $\alpha=0$ je:

$$I_{PRMS} = \frac{2U}{\omega L} = I_{PAV} \sqrt{2}$$

Efektivna vrednost struje potrošača

MONOFAZNI POLUTALASNI KONTROLISANI ISPRAVLJAČI

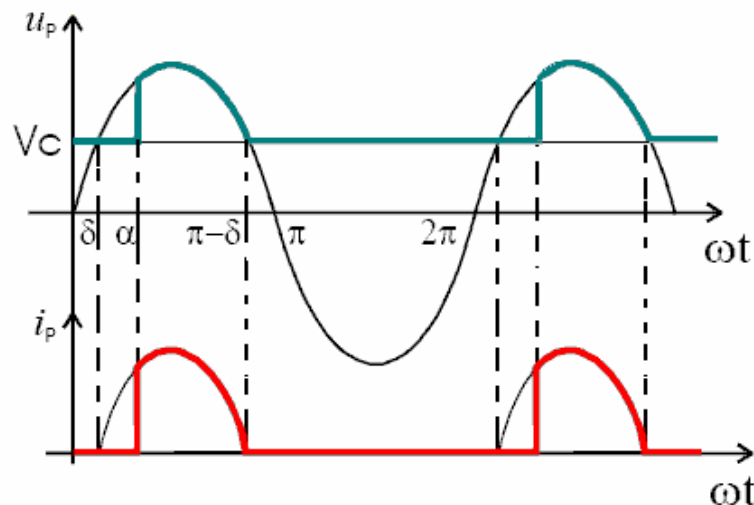
za kontrolu pujenja baterija i akumulatora



Tiristor se može uključiti samo kad je $u > V_c$ jer je tada napon na tiristoru pozitivan, tj. ne pre ugla δ za koji je:

$$U\sqrt{2} \sin \delta = V_c$$

$$m = \sin \delta = \frac{V_c}{U\sqrt{2}}$$



Dakle opseg upravljanja za α je

$$\delta < \alpha < \pi - \delta,$$

odnosno

$$\arcsin(m) < \alpha < \pi - \delta.$$

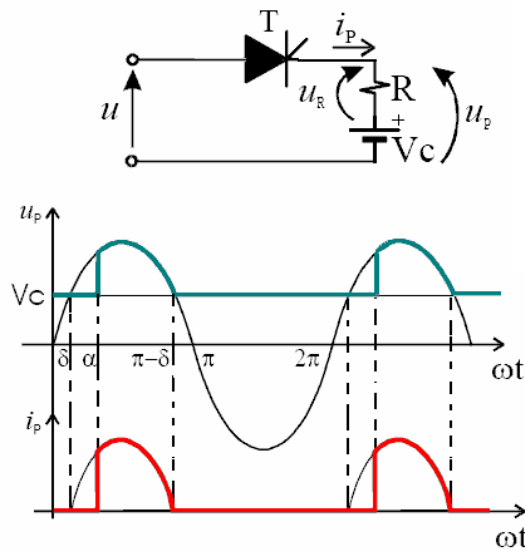
Tiristor se gasi za $u < V_c$

Kada je tiristor uključen kroz potrošač teče struja:

$$i_p = \frac{u_R}{R} = \frac{1}{R}(u - V_c) = \frac{1}{R}(U\sqrt{2} \sin \omega t - mU\sqrt{2}) \Rightarrow$$

$$\Rightarrow i_p = \frac{U\sqrt{2}}{R}(\sin \omega t - m)$$

ANALIZA I PRORAČUNI



Srednja vrednost struje potrošača

$$I_{PAV} = \frac{1}{T} \int_0^T i_p dt = \frac{\omega}{2\pi} \int_{\alpha/\omega}^{(\pi-\delta)/\omega} \frac{U\sqrt{2}}{R} (\sin \omega t - m) dt = \frac{1}{2\pi} \frac{U\sqrt{2}}{R} [(-\cos \omega t) \Big|_{\alpha}^{\pi-\delta} - m(\pi - \delta - \alpha)] \Rightarrow$$

$$\Rightarrow I_{PAV} = \frac{1}{2\pi} \frac{U\sqrt{2}}{R} [\cos \delta + \cos \alpha - m(\pi - \delta - \alpha)] = \frac{1}{2\pi} \frac{U\sqrt{2}}{R} [\cos \alpha + \sqrt{1-m^2} - m(\pi - \delta - \alpha)]$$

Efektivna vrednost struje potrošača

$$I_{PRMS} = \sqrt{\frac{1}{T} \int_0^T i_p^2 dt} = \frac{U\sqrt{2}}{R} \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\pi-\delta} (\sin \omega t - m)^2 d(\omega t)} = \dots$$

Srednja vrednost napona potrošača

$$U_{PAV} = \frac{1}{T} \int_0^T u_p dt = Vc + \frac{1}{T} \int_0^T u_R dt = Vc + \frac{R}{T} \int_0^T i_p dt = Vc + R I_{PAV}$$

Efektivna vrednost napona potrošača

$$U_{PRMS} = \sqrt{\frac{1}{T} \int_0^T u_p^2 dt} = \sqrt{\frac{1}{T} \int_0^T (Vc + Ri)^2 dt} = \dots = \sqrt{Vc^2 + 2Vc R I_{PAV} + (R \cdot I_{PRMS})^2}$$

Izračunavanje snage isporučene potrošaču

$$P = \frac{1}{T} \int_0^T u_p i_p dt = \frac{1}{T} \int_0^T (Vc + u_R) i_p dt = \frac{1}{T} \int_0^T Vc i_p dt + \frac{1}{T} \int_0^T R i_p^2 dt$$

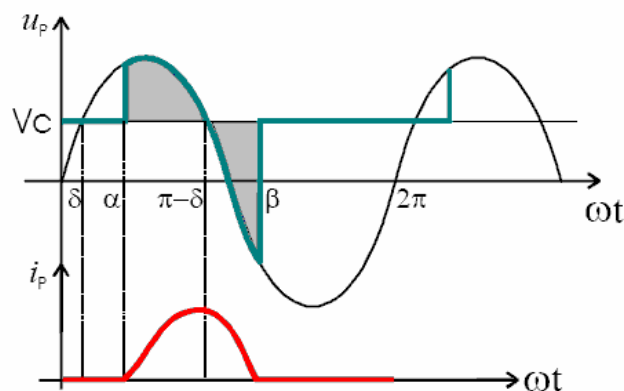
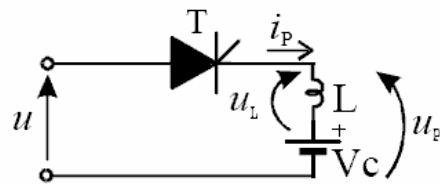
$$P = Vc I_{PAV} + R I_{PRMS}^2$$

Faktor snage izvora

$$\lambda = \frac{P}{U I_{PRMS}} = \frac{Vc I_{PAV} + R I_{PRMS}^2}{U I_{PRMS}}$$

MONOFAZNI POLUTALASNI KONTROLISANI ISPRAVLJAČI

za kontrolu punjenja baterija i akumulatora, sa PRIGUŠNICOM



$$U\sqrt{2} \sin \delta = Vc$$

$$m = \frac{Vc}{U\sqrt{2}} = \sin \delta$$

Srednja vrednost struje potrošača

$$IPAV = \frac{1}{T} \int_0^T i_P \cdot dt = \frac{\omega}{2\pi} \int_{\alpha/\omega}^{\beta/\omega} \frac{U\sqrt{2}}{\omega L} [\cos \alpha - \cos \omega t - m(\omega t - \alpha)] dt$$

$$IPAV = \frac{U\sqrt{2}}{\omega L} \frac{1}{2\pi} [(\beta - \alpha) \cdot \cos \alpha + \sin \alpha - \sin \beta - \frac{m(\beta - \alpha)^2}{2}]$$

Srednja vrednost napona potrošača

$$UPAV = \frac{1}{T} \int_0^T u_P dt = \frac{1}{T} \int_0^T (Vc + u_L) dt = Vc + \frac{1}{T} \int_0^T u_L dt = Vc$$

Aktivna snaga razvijena na potrošaču

$$P = \frac{1}{T} \int_0^T u_P i_P dt = \frac{1}{T} \int_0^T (Vc + u_L) i_P dt = Vc \frac{1}{T} \int_0^T i_P dt + \frac{1}{T} \int_0^T u_L \cdot i_P dt$$

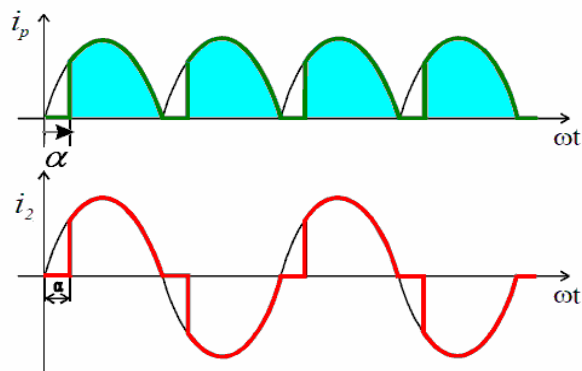
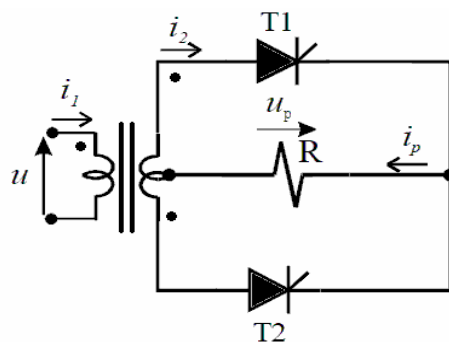
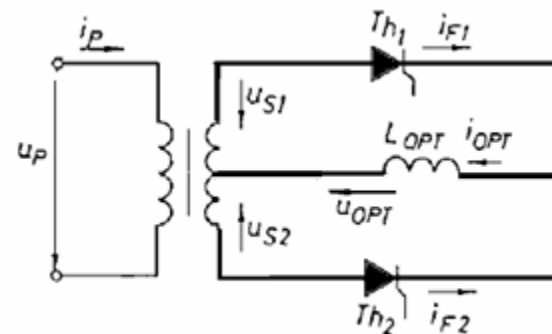
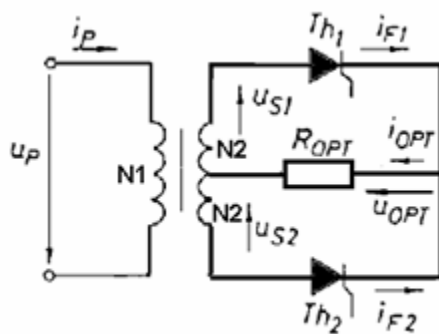
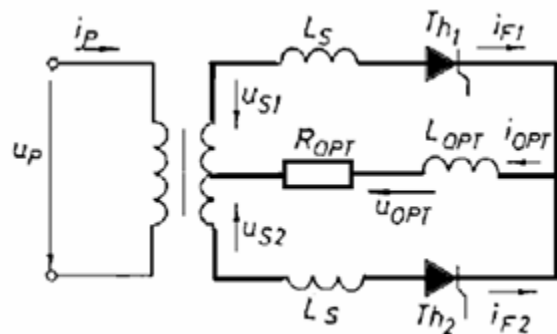
$$P = Vc IPAV + 0 = Vc IPAV$$

$$i_P = \frac{1}{L} \int_0^t u_L dt = \frac{1}{L} \int_{\alpha/\omega}^{\omega t} (U\sqrt{2} \sin \omega t - Vc) dt = \frac{U\sqrt{2}}{\omega L} \int_{\alpha}^{\omega t} (\sin \omega t - m) d(\omega t) = \frac{U\sqrt{2}}{\omega L} [\cos \alpha - \cos \omega t - m(\omega t - \alpha)]$$

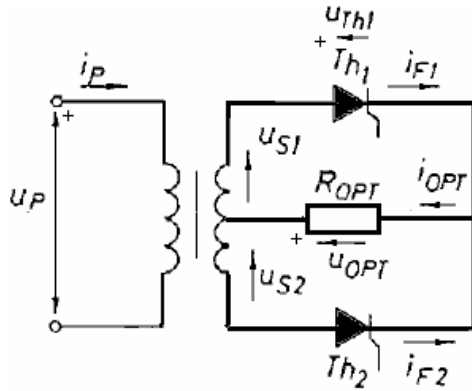
Struja dostiže maksimum za $\omega t = \pi - \delta$, kada je $u = Vc$ i zatim počinje da opada. Za neki ugao β struja postaje nula. Ugao β se dobija rešavanjem jednačine:

$$i_P = 0 \Rightarrow \cos \alpha - \cos \beta - m(\beta - \alpha) = 0 \Rightarrow m(\beta - \alpha) = \cos \alpha - \cos \beta$$

MONOFAZNI PUNOTALASNI ISPRAVLJAČ SA TRANSFORMATOROM SA SREDNJOJ TAČKOM



ANALIZA RADA



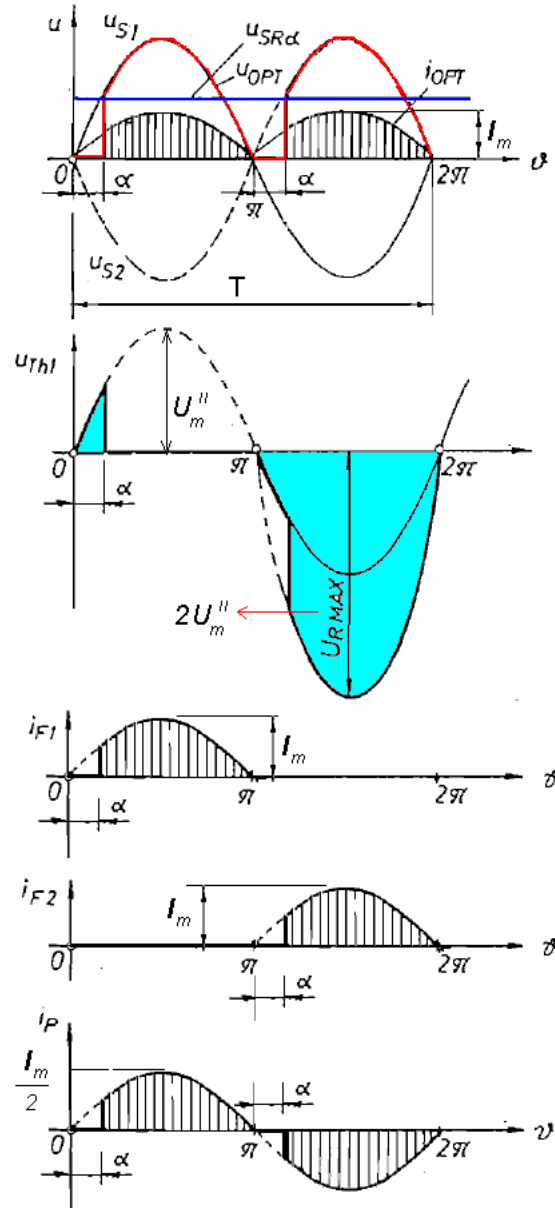
$$U_{SR} = \frac{1}{\pi} \int_{\alpha}^{\pi} U_m'' \cdot \sin \theta d\theta = \frac{U_m''}{\pi} \int_{\alpha}^{\pi} \sin \theta d\theta = \frac{U_m''}{\pi} (1 + \cos \alpha) = \frac{U'' \sqrt{2}}{\pi} (1 + \cos \alpha)$$

$$I_{SR} = \frac{U_{SR}}{R_{OPT}} = \frac{U'' \sqrt{2}}{\pi \cdot R_{OPT}} (1 + \cos \alpha)$$

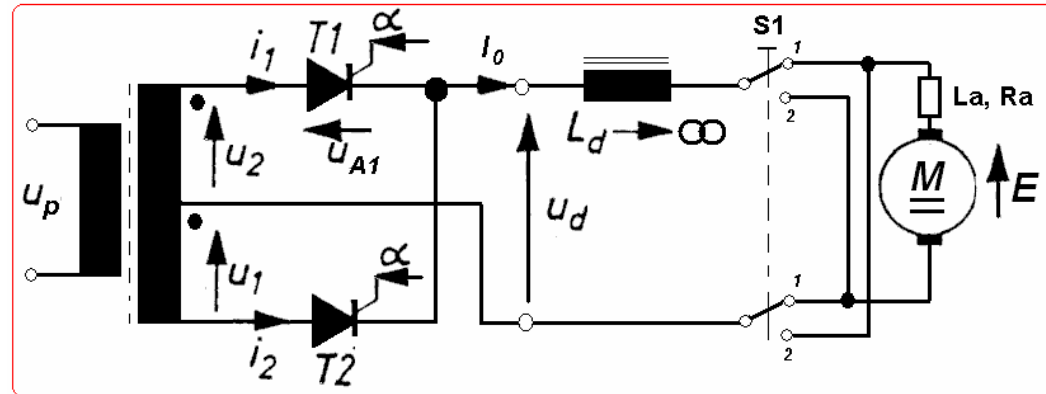
$$I_{FSR} = \frac{1}{2\pi} \int_{\alpha}^{\pi} I_m'' \cdot \sin \theta d\theta = \frac{U_m''}{R \cdot 2\pi} \int_{\alpha}^{\pi} \sin \theta d\theta = \frac{U_m''}{R \cdot 2\pi} (1 + \cos \alpha) = \frac{U'' \sqrt{2}}{2\pi R} (1 + \cos \alpha)$$

$$I_{Feff} = \sqrt{\frac{1}{2\pi} \cdot \int_{\alpha}^{\pi} (I_m'' \cdot \sin \theta)^2 d\theta} = \sqrt{\frac{I_m''^2}{2\pi} \cdot \int_{\alpha}^{\pi} \sin^2 \theta d\theta}$$

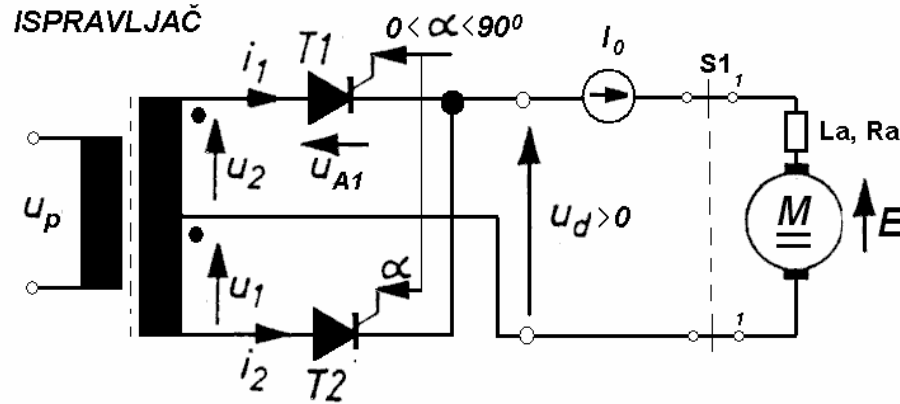
$$I_{Feff} = \frac{U''}{R\sqrt{2}} \cdot \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \cdot \sin 2\alpha} = \frac{I''}{\sqrt{2}} \cdot \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \cdot \sin 2\alpha}$$



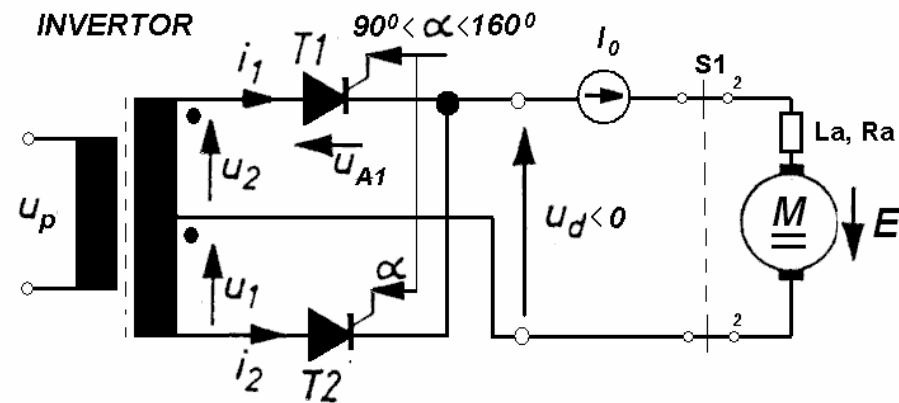
MONOFAZNI PUNOTALASNI ISPRAVLJAČ SA TRANSFORMATOROM SA SREDNJOM TAČKOM ZA POBUDU DC MOTORA



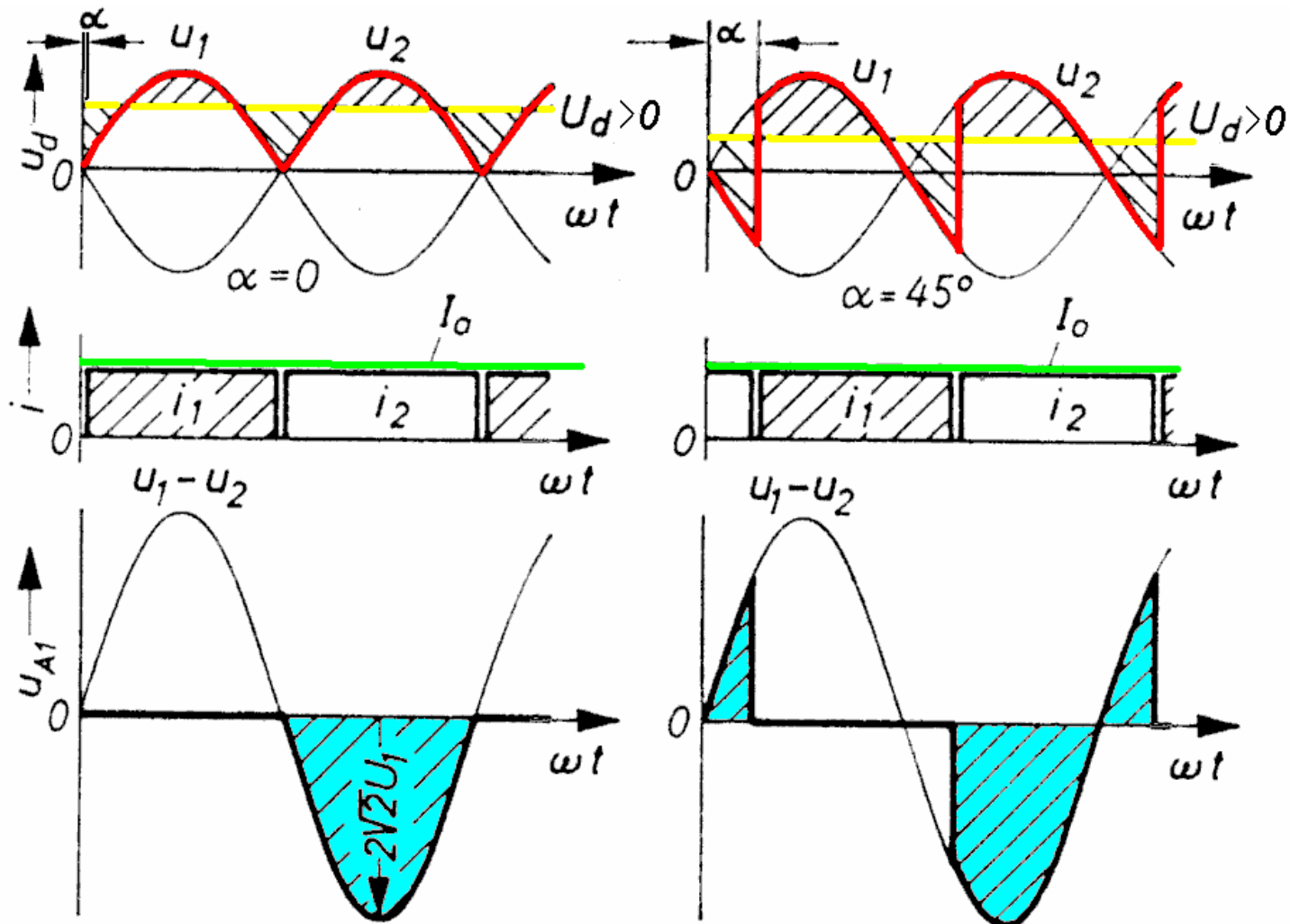
ISPRAVLJAČ



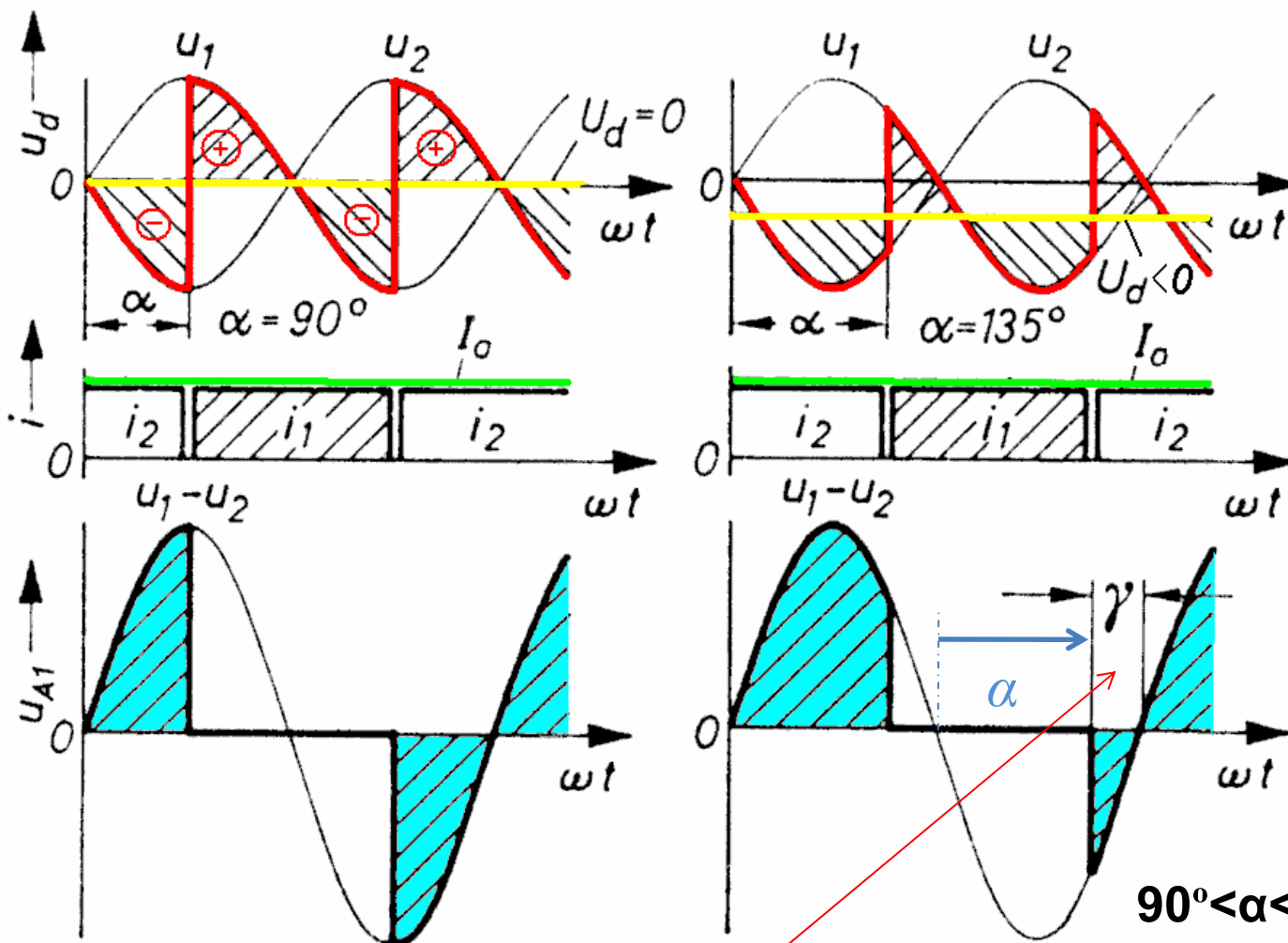
INVERTOR



ANALIZA RADA I TALASNI OBLICI za $U_d > 0$



ANALIZA RADA I TALASNI OBLICI za $U_d \leq 0$



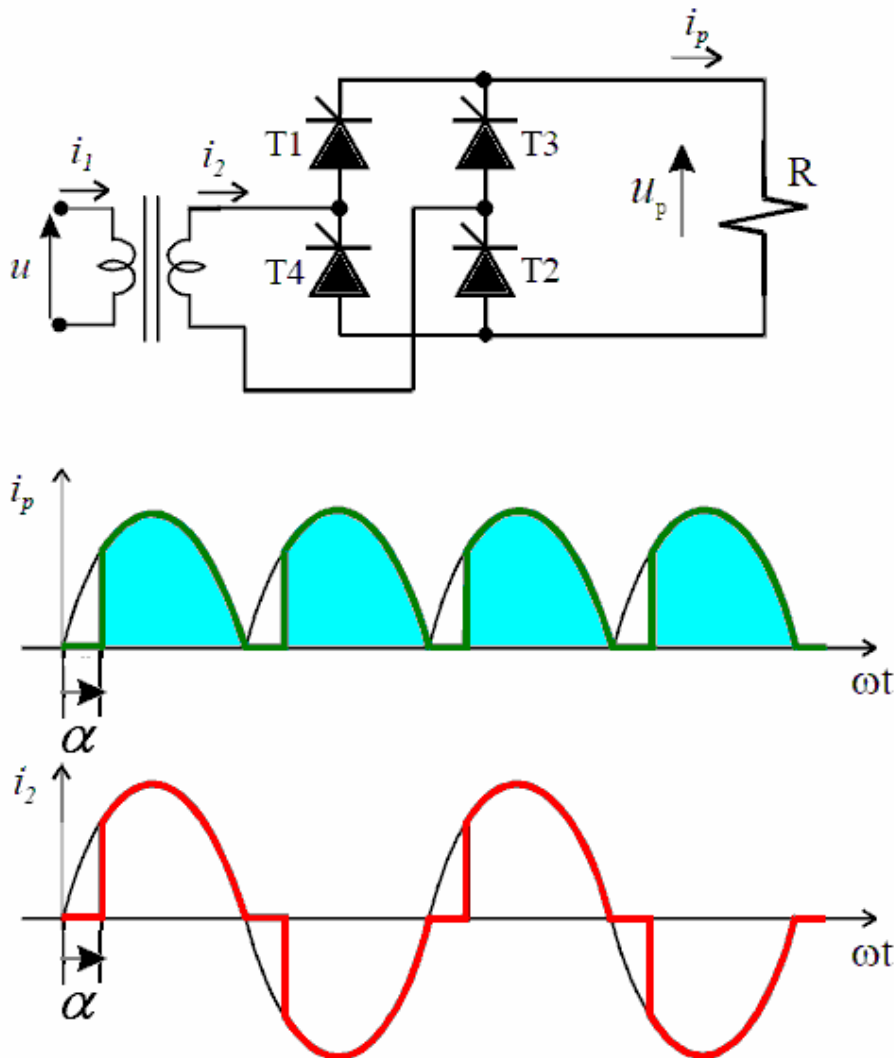
$\gamma \approx 10 \dots 20^\circ$ - ograničenje trajanja inverzne polarizacije tiristora

$90^\circ < \alpha < 160^\circ \dots 170^\circ$
ograničenje ugla upravljanja u invertorskom režimu

$$\alpha + \gamma \approx 180^\circ$$

$\gamma > \omega t_0$ t_0 - VREME ODMORA TIRISTORA

MONOFAZNI PUNOTALASNI MOSNI ISPRAVLJAČ

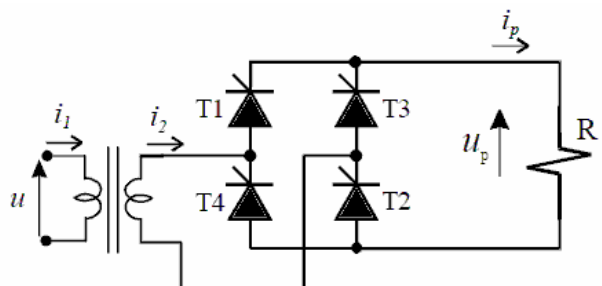


U toku svake poluperiode napona izvora provode po dva tiristora što rezultuje punotalasnim ispravljanjem i simetričnim oblikom struje izvora.

Na ovaj način struja izvora nema jednosmernu komponentu, pa se može upotrebiti transformator kao izvor naizmeničnog napona.

Kod ovog ispravljača postoje dva impulsa struje potrošača za vreme jedne periode napona izvora pa se može okarakterisati kao "dvopulsni".

MONOFAZNI PUNOTALASNI MOSNI ISPRAVLJAČ SA OMSKIM OPTEREĆENJEM-izračunavanje srednjih i efektivnih vrednosti



SREDNJA VREDNOST STRUJE POTROŠAČA

$$I_{PAV} = 2 \frac{U\sqrt{2}}{2\pi R} (1 + \cos \alpha) = \frac{U}{R} \frac{\sqrt{2}}{\pi} (1 + \cos \alpha)$$

EFEKTIVNA VREDNOST STRUJE POTROŠAČA

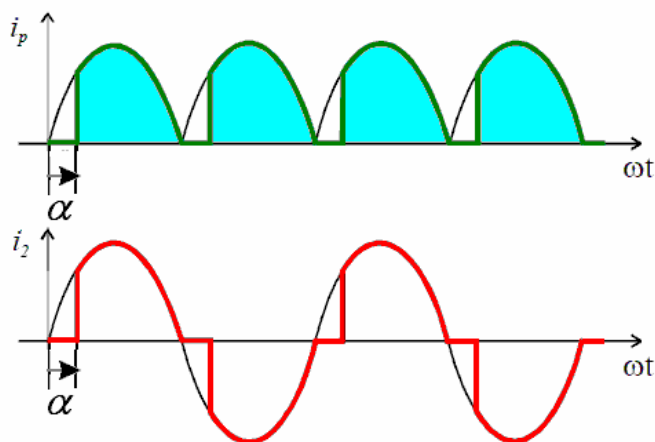
$$I_{PRMS} = \sqrt{2} \frac{U}{R\sqrt{2}} \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \sin 2\alpha} = \frac{U}{R} \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \sin 2\alpha}$$

SREDNJA VREDNOST NAPONA POTROŠAČA

$$U_{PAV} = 2U_{PAV1/2} = 2 \frac{U\sqrt{2}}{2\pi} (1 + \cos \alpha) = U \frac{\sqrt{2}}{\pi} (1 + \cos \alpha)$$

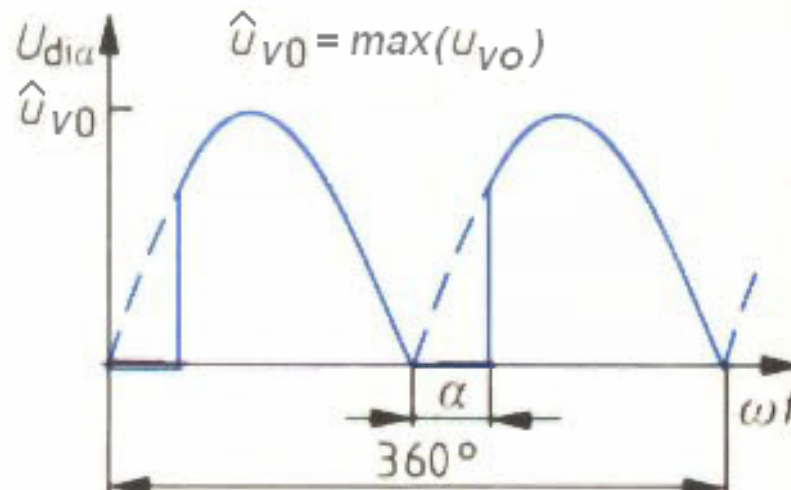
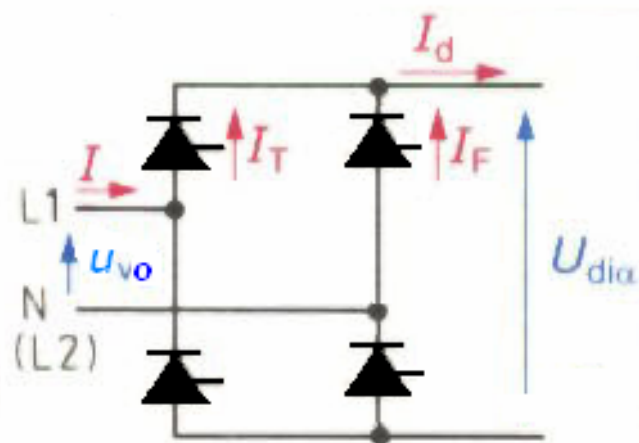
EFEKTIVNA VREDNOST NAPONA POTROŠAČA

$$U_{PRMS} = \sqrt{2} U_{PRMS1/2} = \sqrt{2} \frac{U}{\sqrt{2}} \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \sin 2\alpha} = U \sqrt{1 - \frac{\alpha}{\pi} + \frac{1}{2\pi} \sin 2\alpha}$$



UPRAVLJAČKA KARAKTERISTIKA (potrošač omska otpornost)

MONOFAZNI PUNO UPRAVLJIVI DVO-IMPULSNI MOSNI SPOJEVI

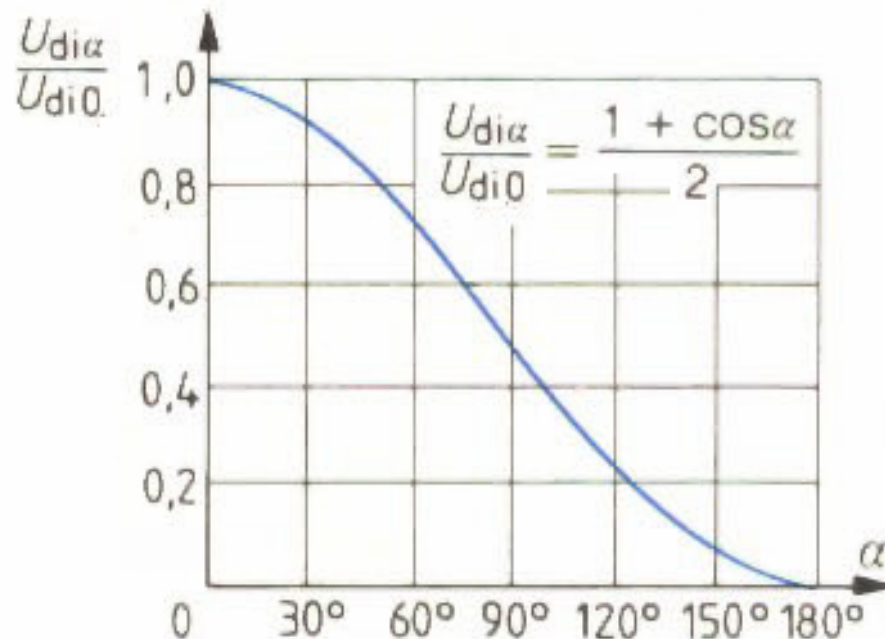


$$U_{v0} = \text{RMS}(u_{v0})$$

$$\frac{U_{dia}}{U_{di0}} = \frac{1 + \cos\alpha}{2}$$

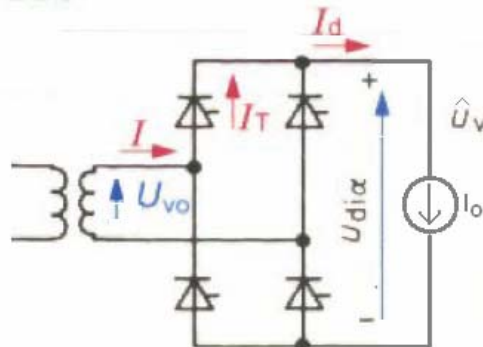
$$U_{dio} = \frac{2\sqrt{2}}{\pi} U_{v0}$$

$$U_{dio} = 0,9 \cdot U_{v0}$$

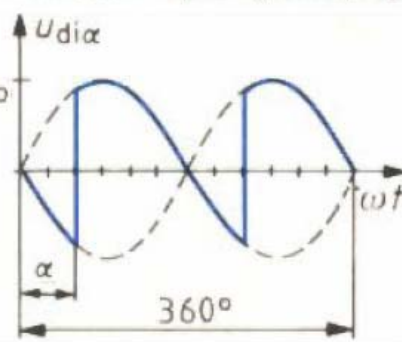


MONOFAZNI PUNOTALASNI MOSNI ISPRAVLJAČ SA JAKO INDUKTIVNIM OPTEREĆENJEM ($L \rightarrow \infty$) -izračunavanje srednje vrednosti izlaznog napona

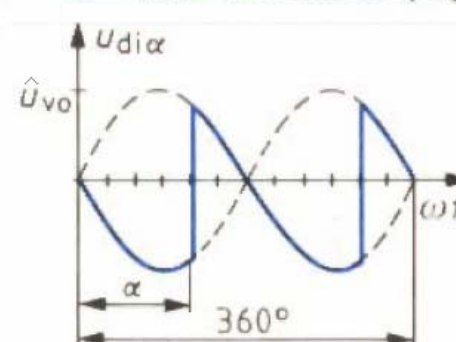
Dvoimpulsni mosni spoj
B2C



$\alpha = 60^\circ$ ispravljački pogon



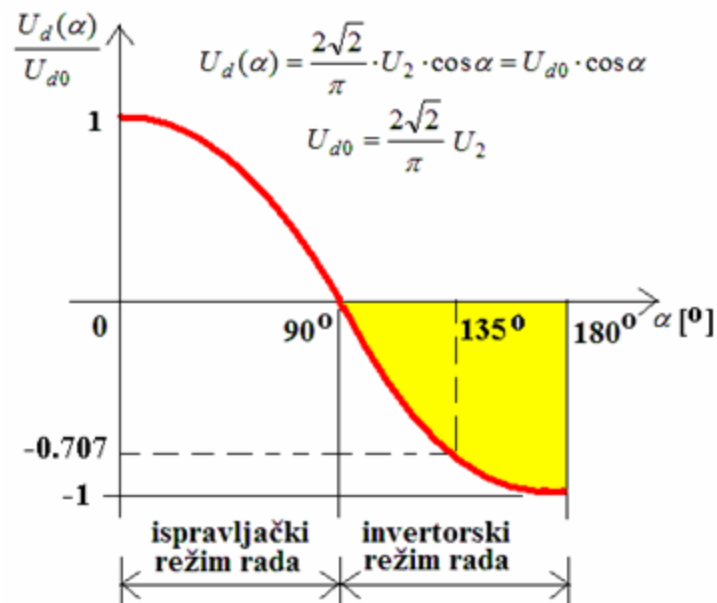
$\alpha = 120^\circ$ invertorski pogon



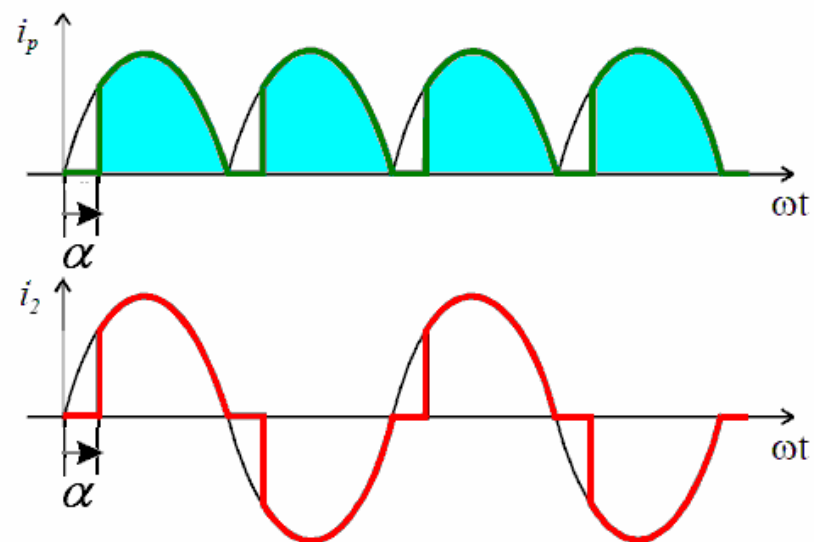
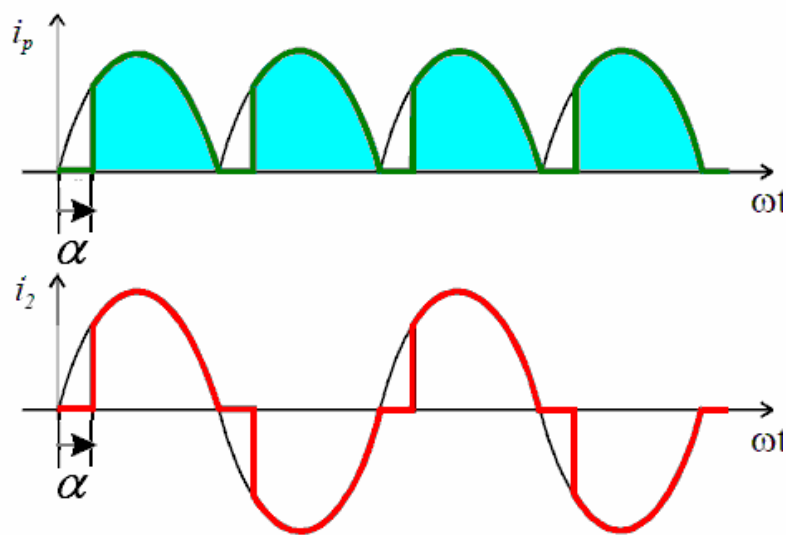
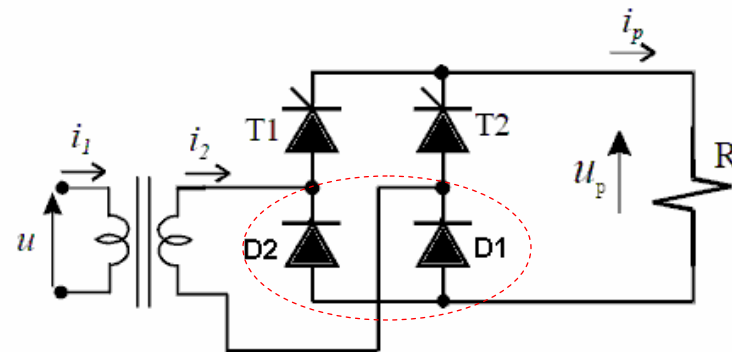
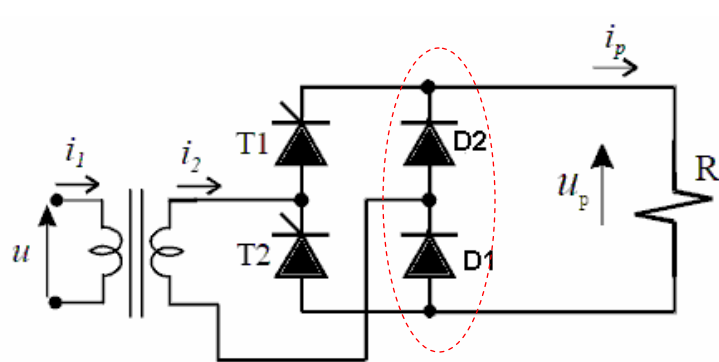
$$\frac{U_{dio}}{U_{vo}} = 0,90$$

$$\frac{U_{dia}}{U_{dio}} = \cos \alpha$$

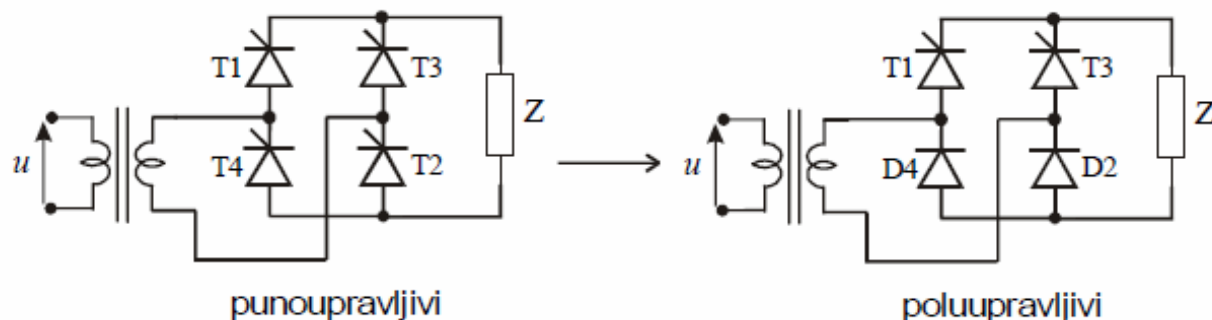
UPRAVLJAČKA
KARAKTERISTIKA



MONOFAZNI PUNOTALASNI POLUUPRAVLJIVI MOSNI ISPRAVLJAČI



MONOFAZNI PUNOTALASNI POLUUPRAVLJIVI MOSNI ISPRAVLJAČI- analiza rada



- U slučaju kad je $Z=R$ (čista omska otpornost) talasni oblici izlaznog napona su isti za oba tipa ispravljača.
- U slučaju kad je opterećenje strujni ponor razlikovaće se talasni oblici izlaznog napona

Kada vode T1 i D2:

$$i_2 = i_{T1} = i_{D2} = I, i_{T3} = i_{D4} = 0, u_P = u_2$$

Kada $u_2 < 0$ provešće D4, D2 prestaje da provodi, pa se struja I zatvara kroz T1 i D4:

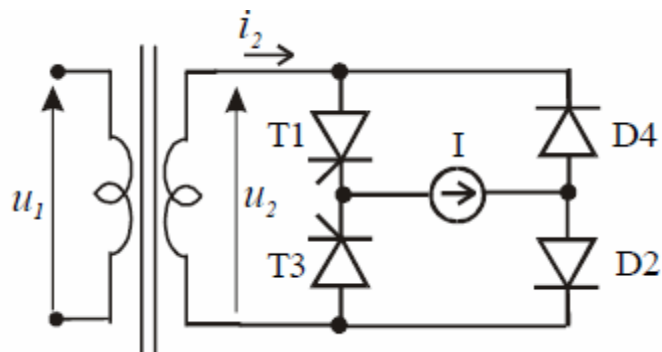
$$i_2 = i_{T3} = i_{D2} = 0, i_{T1} = i_{D4} = I, u_P = 0$$

Kada se uključe T3, gasi se T1, pa se struja I zatvara kroz T3, potrošač i D4:

$$i_2 = -I, i_{T3} = i_{D4} = I, i_{T1} = i_{D2} = 0, u_P = -u_2$$

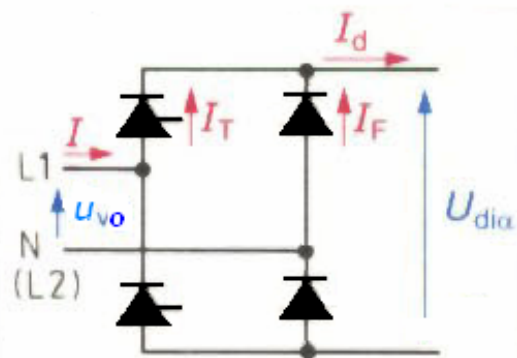
Kada $u_2 > 0$ provešće D2, D4 prestaje da provodi, pa se struja I zatvara kroz T3 i D2:

$$i_2 = i_{T1} = i_{D4} = 0, i_{T3} = i_{D2} = I, u_P = 0$$



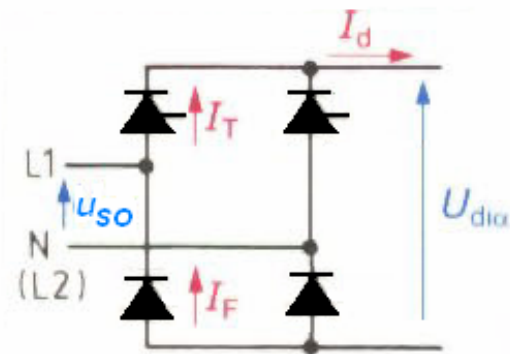
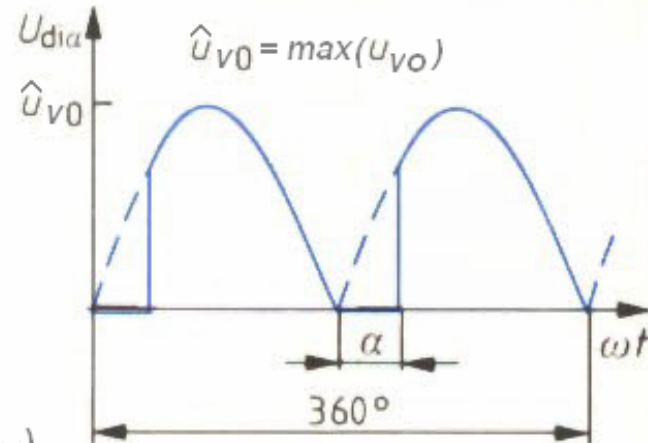
UPRAVLJAČKA KARAKTERISTIKA

MONOFAZNI POLU UPRAVLJIVI DVO-IMPULSNI MOSNI SPOJEVI



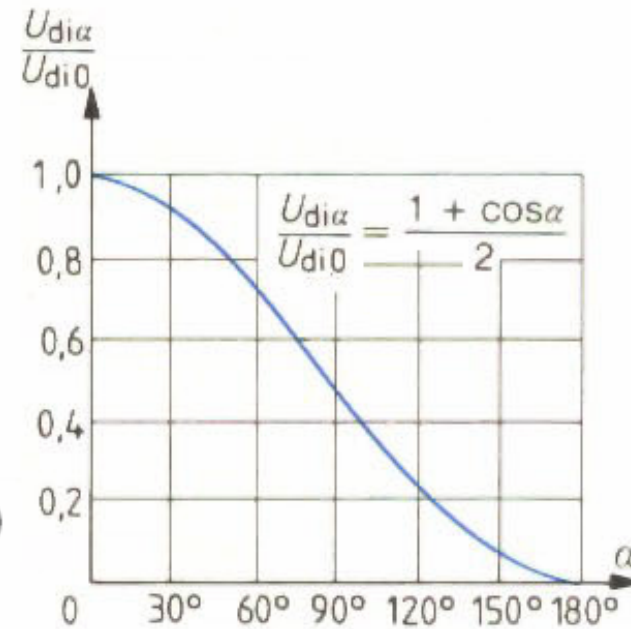
$$U_{dio} = \frac{2\sqrt{2}}{\pi} U_{v0} \quad U_{v0} = \text{RMS}(u_{v0})$$

$$U_{dio} = 0,9 \cdot U_{v0}$$

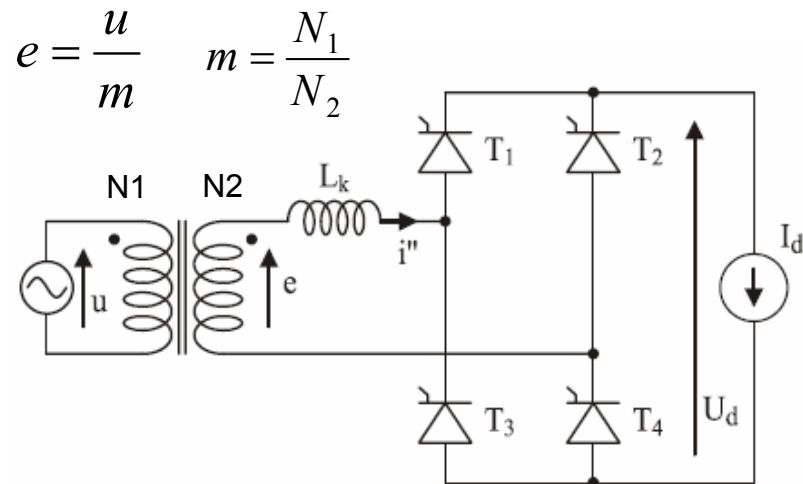


$$U_{dio} = \frac{2\sqrt{2}}{\pi} U_{so} \quad U_{so} = \text{RMS}(u_{so})$$

$$U_{dio} = 0,9 \cdot U_{so}$$



EFEKAT RASIPNE INDUKTIVNOSTI

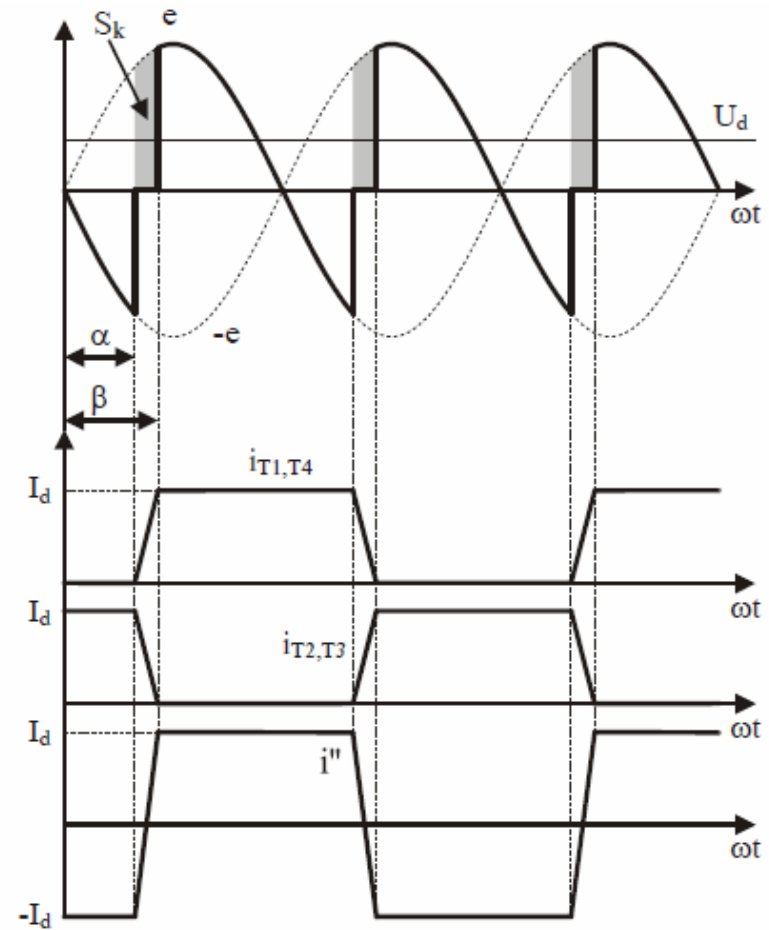


$$e = E\sqrt{2} \cdot \sin \omega t \quad X_k = \omega \cdot L_k$$

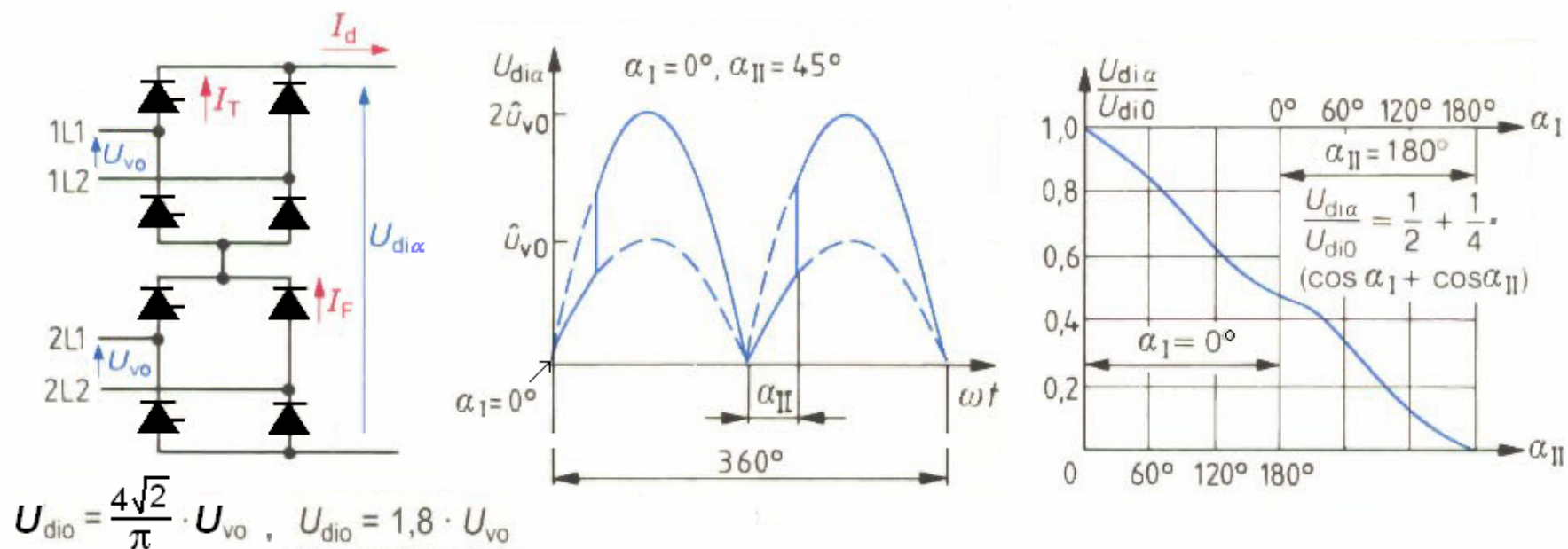
$$S_k = 2 \cdot L_k \cdot I_d$$

SREDNJA VREDNOST IZLAZNOG NAPONA

$$U_d = \frac{2\sqrt{2}}{\pi} \cdot E \cdot \cos \alpha - \frac{2}{\pi} \cdot X_k \cdot I_d$$

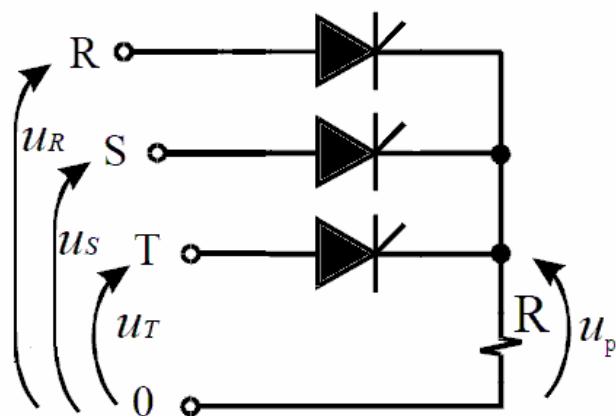


SLEDNO UPRAVLJANJE-SERIJSKI SPOJ DVA POLUUPRAVLJIVA MOSTA



PRIMENA: Regulacija broja obrtaja vučnih motora (električne lokomotive)

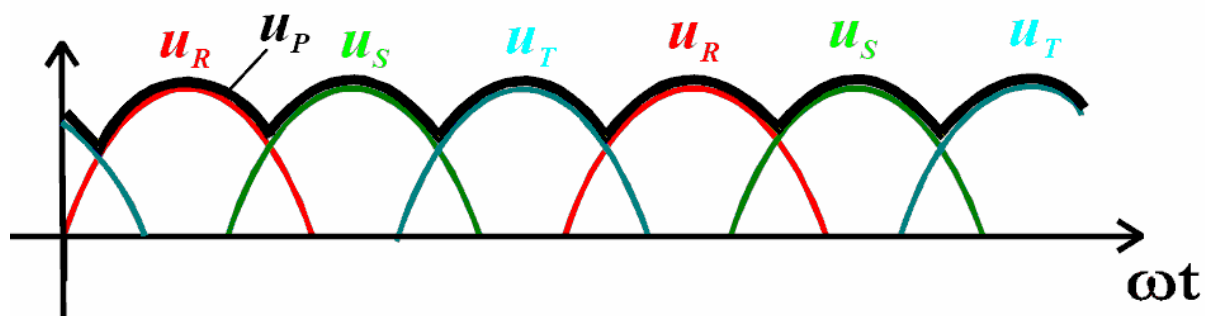
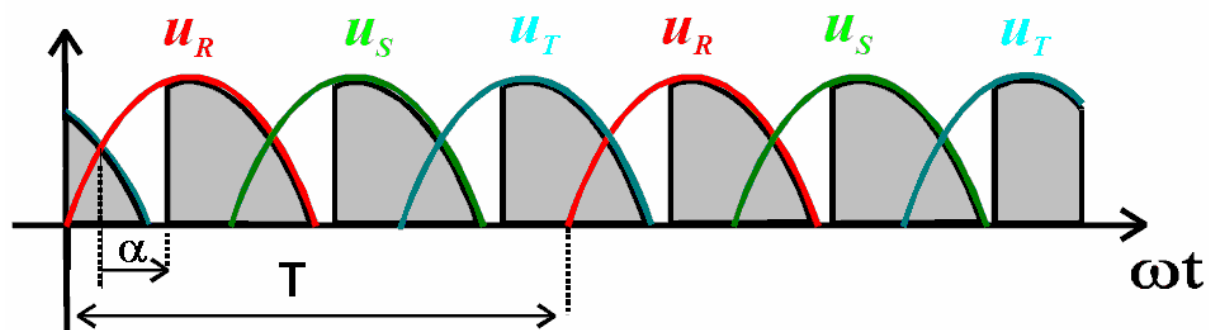
TROFAZNI POLUMOSNI ISPRAVLJAČ sa otpornim opterećenjem



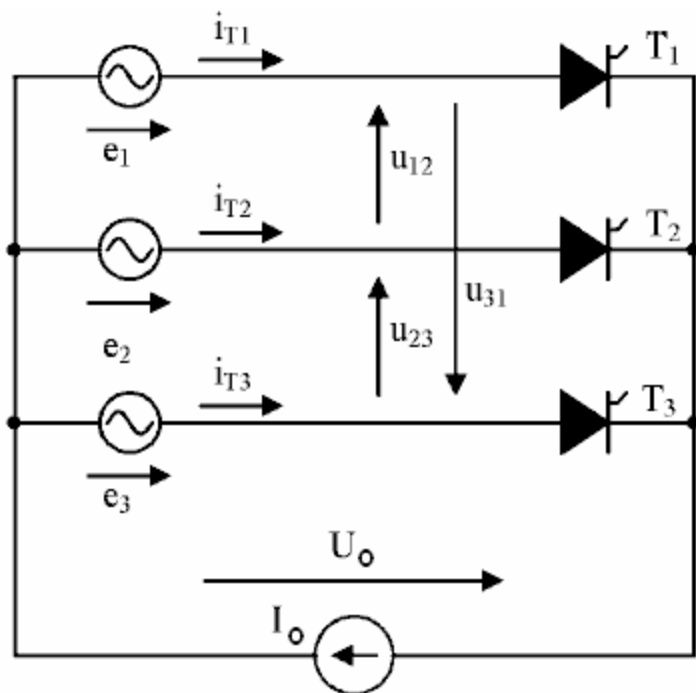
$$u_R = U\sqrt{2} \sin \omega t$$

$$u_S = U\sqrt{2} \sin(\omega t - \frac{2\pi}{3})$$

$$u_T = U\sqrt{2} \sin(\omega t - \frac{4\pi}{3})$$



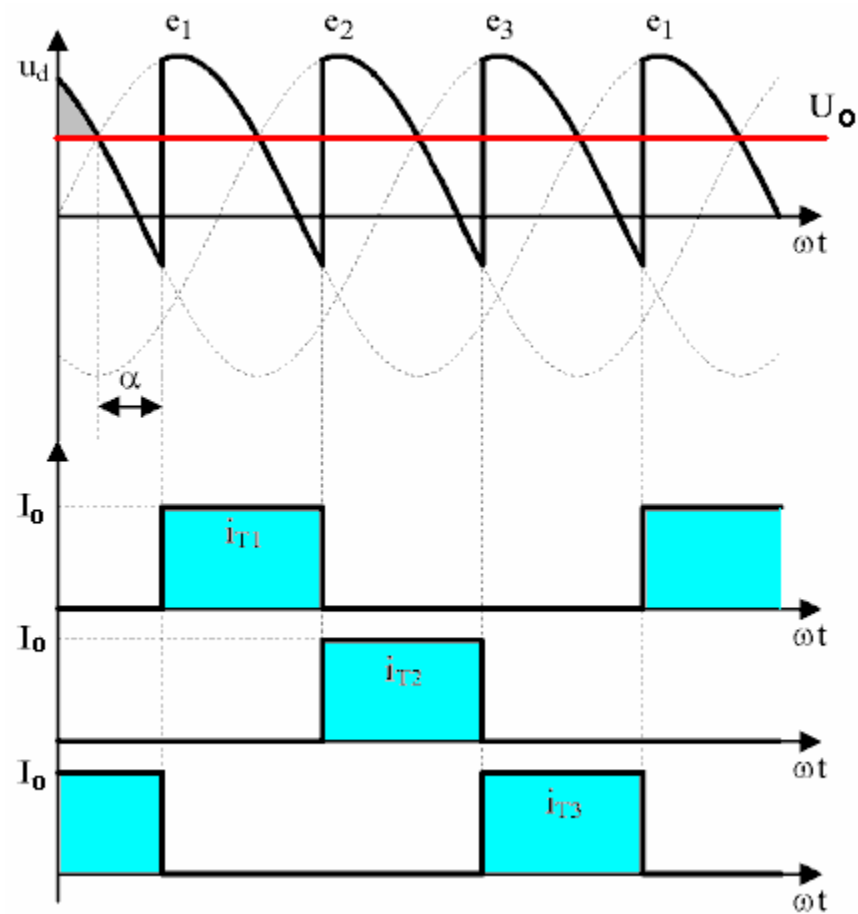
TROFAZNI POLUMOSNI ISPRAVLJAČ sa strujnim ponorom kao opterećenjem



$$e_1 = E\sqrt{2} \cdot \sin \omega t$$

$$e_2 = E\sqrt{2} \cdot \sin(\omega t - 120^\circ)$$

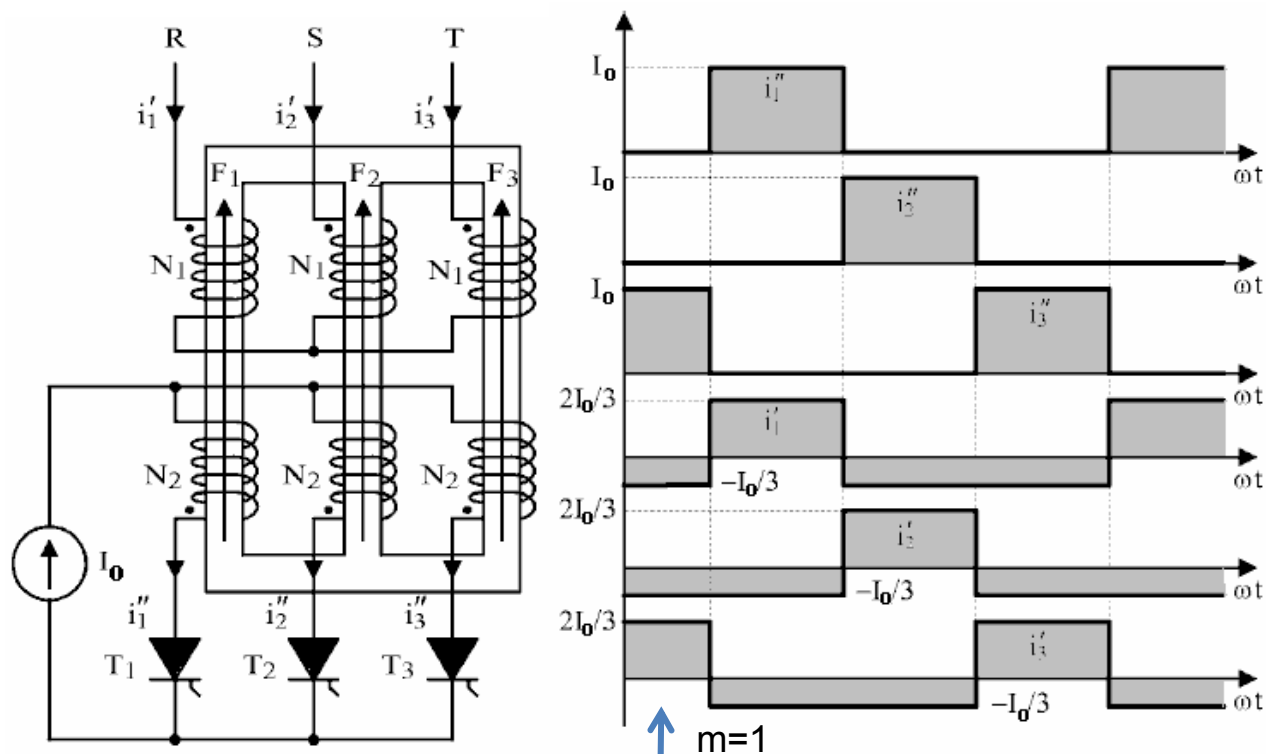
$$e_3 = E\sqrt{2} \cdot \sin(\omega t - 240^\circ)$$



Srednja vrednost izlaznog napona

$$U_o = \frac{3\sqrt{6}}{2\pi} \cdot E \cdot \cos \alpha$$

TROFAZNI POLUMOSNI ISPRAVLJAČ sa strujnim ponorom kao opterećenjem (analiza talasnih oblika struja)



Struje kroz primarne namotaje se mogu odrediti iz uslova da zbir MPS po zatvorenom magnetnom putu bude jednak 0.

Ako se zanemari struja magnećenja transformatora izjednačavanjem MPS za levi i srednji stub se dobija:

$$N_1 i_1' - N_2 i_1'' = N_1 i_2' - N_2 i_2''$$

Slično važi i za levi i desni stub:

$$N_1 i_1' - N_2 i_1'' = N_1 i_3' - N_2 i_3''$$

Treća jednačina:

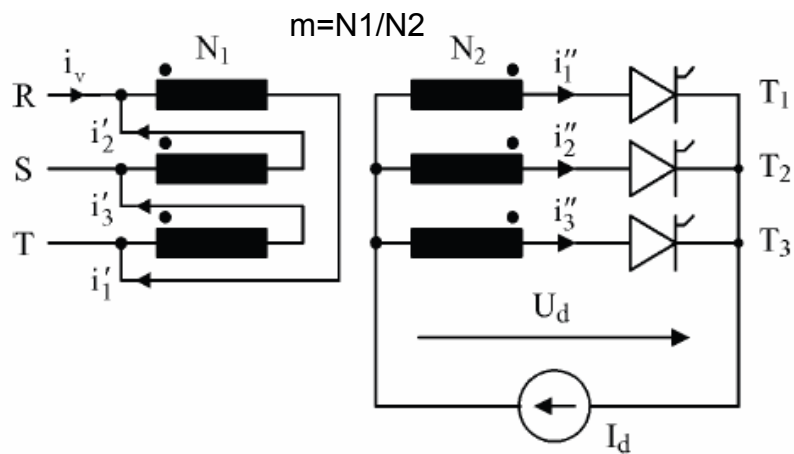
$$i_1' + i_2' + i_3' = 0$$

$$i_1' = \frac{1}{m} \cdot \frac{1}{3} \cdot (2i_1'' - i_2'' - i_3'')$$

$$i_2' = \frac{1}{m} \cdot \frac{1}{3} \cdot (2i_2'' - i_1'' - i_3'')$$

$$i_3' = \frac{1}{m} \cdot \frac{1}{3} \cdot (2i_3'' - i_1'' - i_2'')$$

REŠAVANJEM OVOG
SISTEMA JEDNAČINA SE
DOBIJA



E-EFEKTIVNA VREDNOST FAZNOG NAPONA NA SEKUNDARU

SREDNJA VREDNOST IZLAZNOG NAPONA

$$U_d = \frac{3}{2\pi} \int_{\alpha+\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}+\frac{2\pi}{3}} \sqrt{2}E \sin x \, dx = \frac{3\sqrt{2}E}{2\pi} \cos x \Big|_{\alpha+\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}+\frac{2\pi}{3}} = \frac{3\sqrt{6}E}{2\pi} \cos \alpha$$

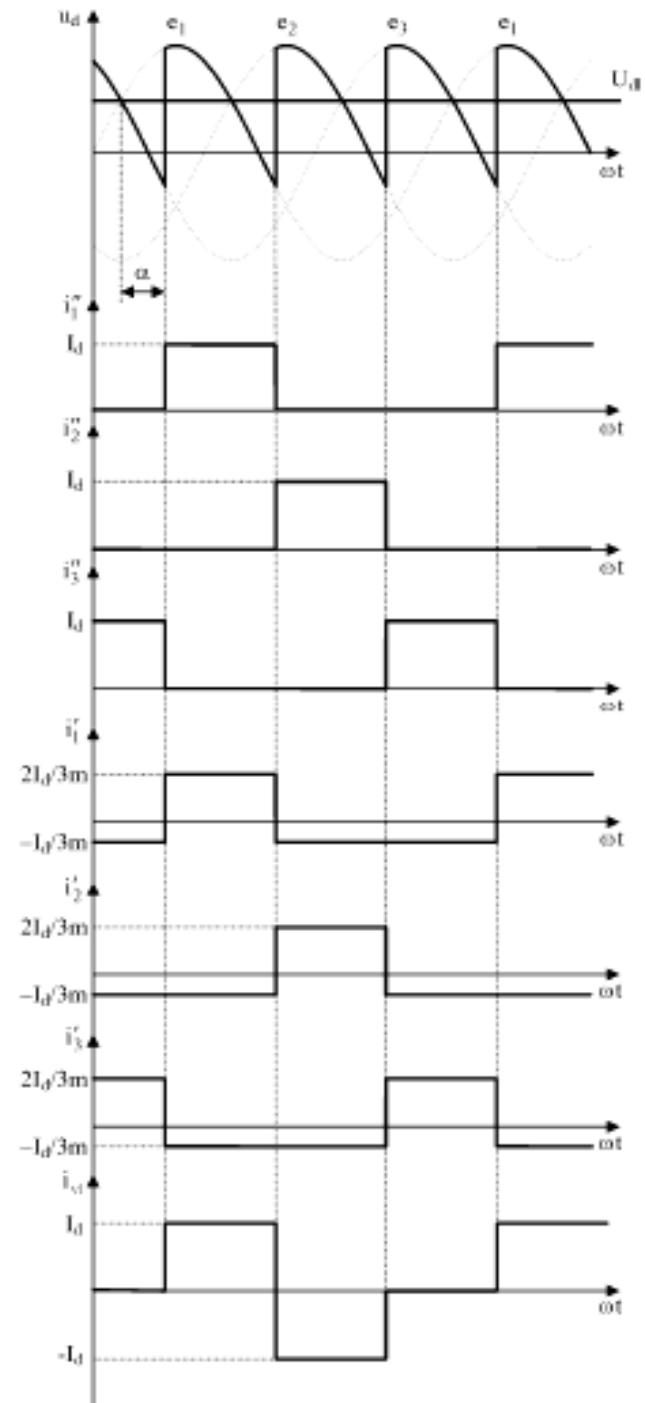
$$U_d = \frac{3\sqrt{6}E}{2\pi} \cos \alpha$$

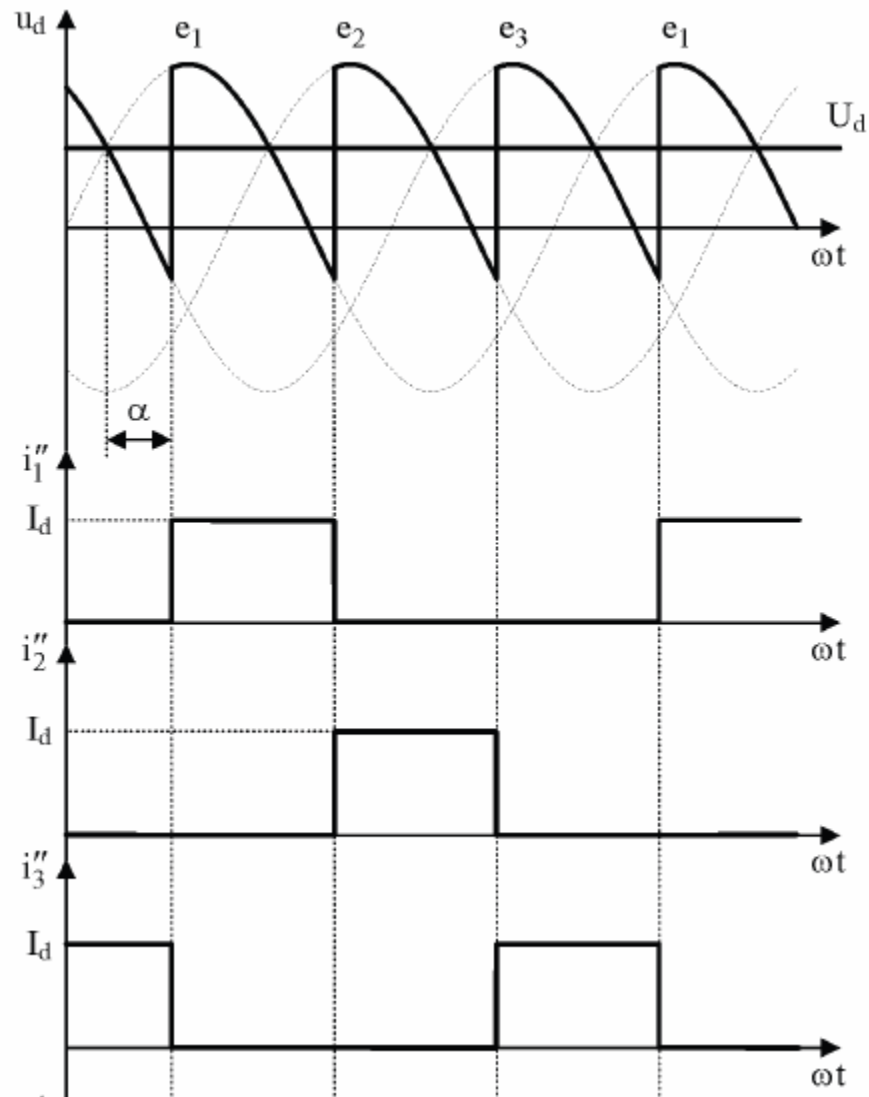
STRUJE PRIMARA:

$$i'_1 = \frac{1}{3m} (2i_1'' - i_2'' - i_3'')$$

$$i'_2 = \frac{1}{3m} (2i_2'' - i_1'' - i_3'')$$

$$i'_3 = \frac{1}{3m} (2i_3'' - i_1'' - i_2'')$$





PRENOSNI ODNOS TRANSFORMATORA

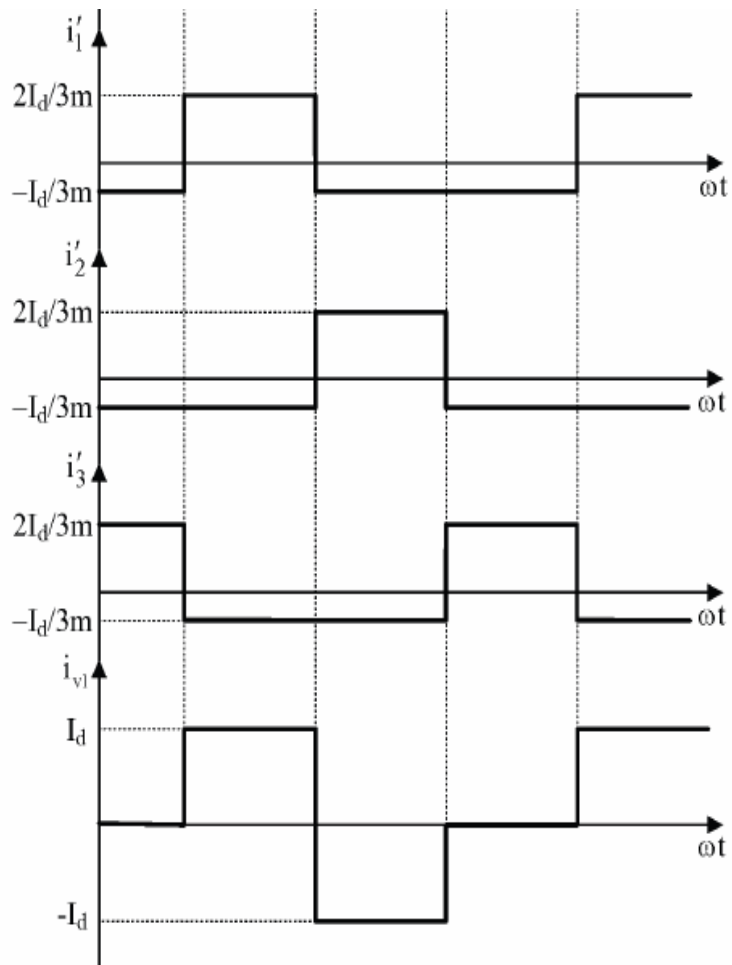
$$m=N1/N2$$

SREDNJA VREDNOST NAPONA NA OPTEREĆENJU

$$U_d = \frac{3\sqrt{6}}{2\pi \cdot m} \cdot E \cdot \cos \alpha$$

EFEKTIVNA VREDNOST STRUJE U NAMOTAJIMA SEKUNDARA

$$I'' = \sqrt{\frac{1}{T} \int_0^{\frac{T}{3}} I_d^2 dt} = \frac{I_d}{\sqrt{3}}$$



EFEKTIVNA VREDNOST STRUJE U NAMOTAJIMA PRIMARA

$$I' = \sqrt{\frac{1}{T} \left(\frac{T}{3} \frac{4I_d^2}{9m^2} + \frac{2T}{3} \frac{I_d^2}{9m^2} \right)} = \sqrt{\frac{1}{3} \frac{I_d^2}{m^2} \left(\frac{4}{9} + \frac{2}{9} \right)} = \frac{\sqrt{2}I_d}{3m}$$

EFEKTIVNA VREDNOST STRUJE DOVODNIM PRIKLJUČCIMA (LINIJSKI PROVODNICMA)

$$I' = \sqrt{\frac{1}{T} \cdot \frac{T}{3} \cdot \frac{2I_d^2}{m^2}} = \sqrt{\frac{2}{3}} \cdot \frac{I_d}{m}$$

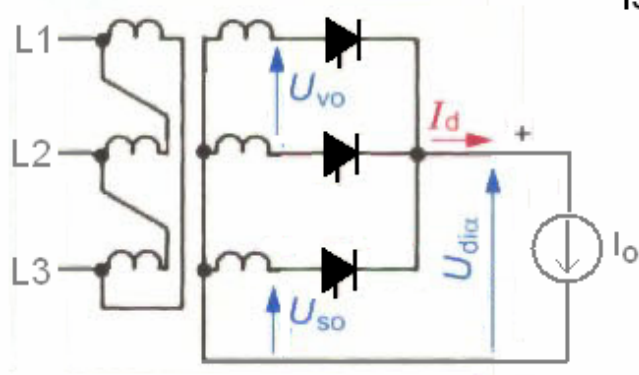
FAKTOR SNAGE ISPRAVLJAČA

$$\lambda = \frac{P}{\sqrt{3}UI_v} = \frac{\frac{3\sqrt{6}}{2\pi} \cdot E \cdot I_d \cdot |\cos \alpha|}{\sqrt{3}mE \cdot \sqrt{\frac{2}{3}} \frac{I_d}{m}} = \frac{3\sqrt{3}}{2\pi} |\cos \alpha|$$

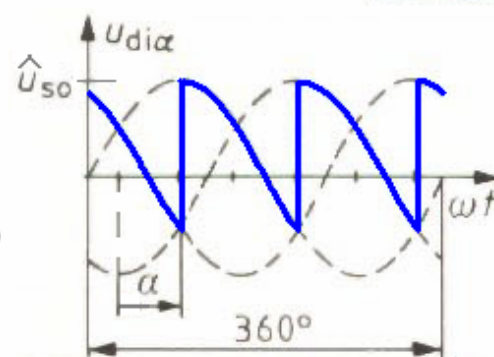
UPRAVLJAČKA KARAKTERISTIKA

TROFAZNI POLUMOSNI ISPRAVLJAČ SA IZVEDENOM NULOM (srednjom tačkom) M3C

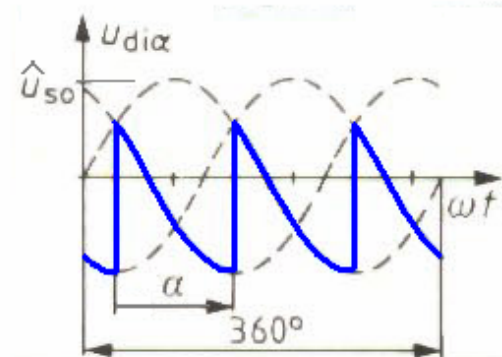
OPTEREĆENJE - STRUJNI PONOR



ISPRAVLJAČKI POGON $\alpha = 60^\circ$



INVERTORSKI POGON $\alpha = 120^\circ$

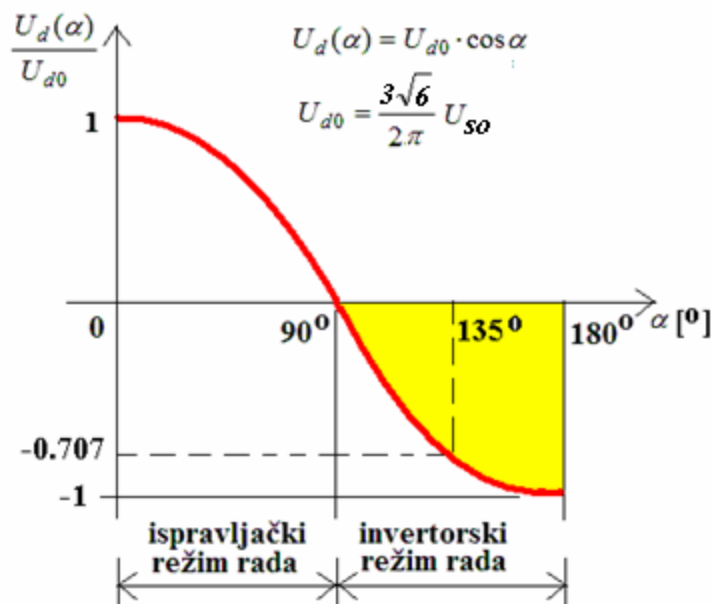


$$\hat{U}_{so} = \max(U_{so})$$

$$\frac{U_{dio}}{U_{vo}} = \frac{3\sqrt{2}}{2\pi} = 0,68 \quad \frac{U_{dia}}{U_{dio}} = \cos \alpha$$

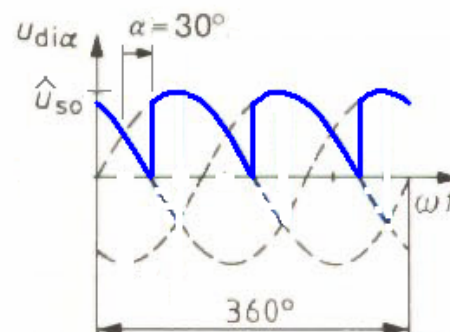
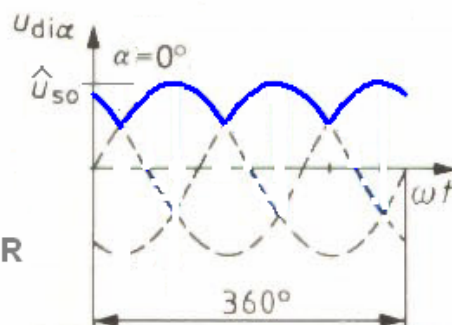
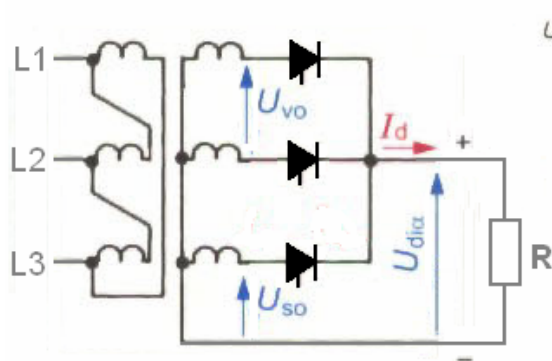
$$U_{dia} = \frac{3\sqrt{2}}{2\pi} U_{vo} \cos \alpha$$

$$U_{dia} = \frac{3\sqrt{6}}{2\pi} U_{so} \cos \alpha$$



UPRAVLJAČKA KARAKTERISTIKA- trofazni polumosni ispravljač sa izvedenom nulom

OPTEREĆENJE-OMSKI OTPOR



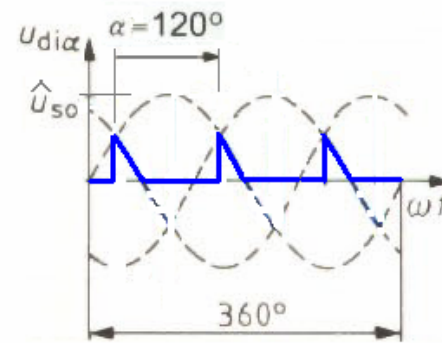
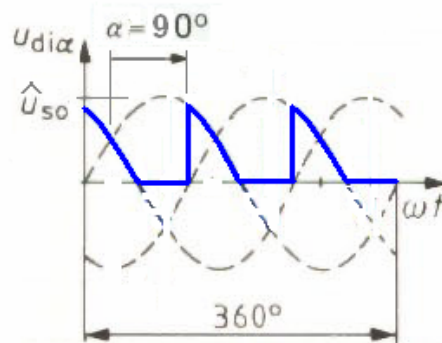
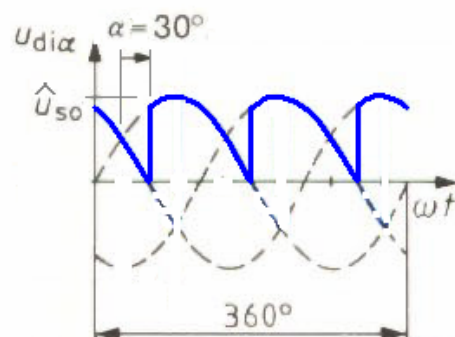
za $0^\circ \leq \alpha \leq 30^\circ$

$$\frac{U_{dio}}{U_{vo}} = \frac{3\sqrt{2}}{2\pi} = 0,68 \quad \frac{U_{dia}}{U_{dio}} = \cos \alpha$$

$$U_{vo} = \sqrt{3} U_{so}$$

$$U_{dia} = \frac{3\sqrt{2}}{2\pi} U_{vo} \cos \alpha$$

$$U_{dia} = \frac{3\sqrt{6}}{2\pi} U_{so} \cos \alpha$$



za $30^\circ \leq \alpha \leq 120^\circ$

$$\frac{U_{dio}}{U_{vo}} = \frac{3\sqrt{2}}{2\pi} = 0,68$$

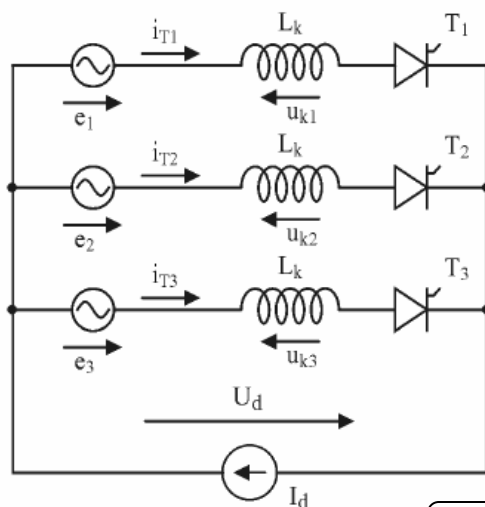
$$U_{vo} = \sqrt{3} U_{so}$$

$$\frac{U_{dia}}{U_{dio}} = 0,58 \cdot [1 + \cos (\alpha + 30^\circ)]$$

$$U_{dia} = \frac{U_{vo}\sqrt{6}}{2\pi} \cdot [1 + \cos (\alpha + 30^\circ)]$$

$$U_{dia} = \frac{3\sqrt{2}}{2\pi} \cdot U_{so} \cdot [1 + \cos (\alpha + 30^\circ)]$$

TROFAZNI POLUMOSNI ISPRAVLJAČ-uticaj rasipne induktivnost L_k



Posmatra se komutacija između T1 i T3

$$I_d = i_{T1} + i_{T3}$$

Diferenciranjem ovog izraza i množenjem sa L_k se dobija:

$$L_k i'_{T3} = -L_k i'_{T1} \Rightarrow u_{k3} = -u_{k1}$$

$$\text{Takođe važi: } e_1 - u_{k1} = e_3 - u_{k3}$$

Napon na komutacionoj prigusnici je:

$$u_{k1} = L_k i'_{T1} = \frac{e_1 - e_3}{2} = \frac{u_{13}}{2} = \frac{\sqrt{6}E}{2} \sin(\omega t)$$

Struja tiristora T1 se dobija rešavanjem integrala:

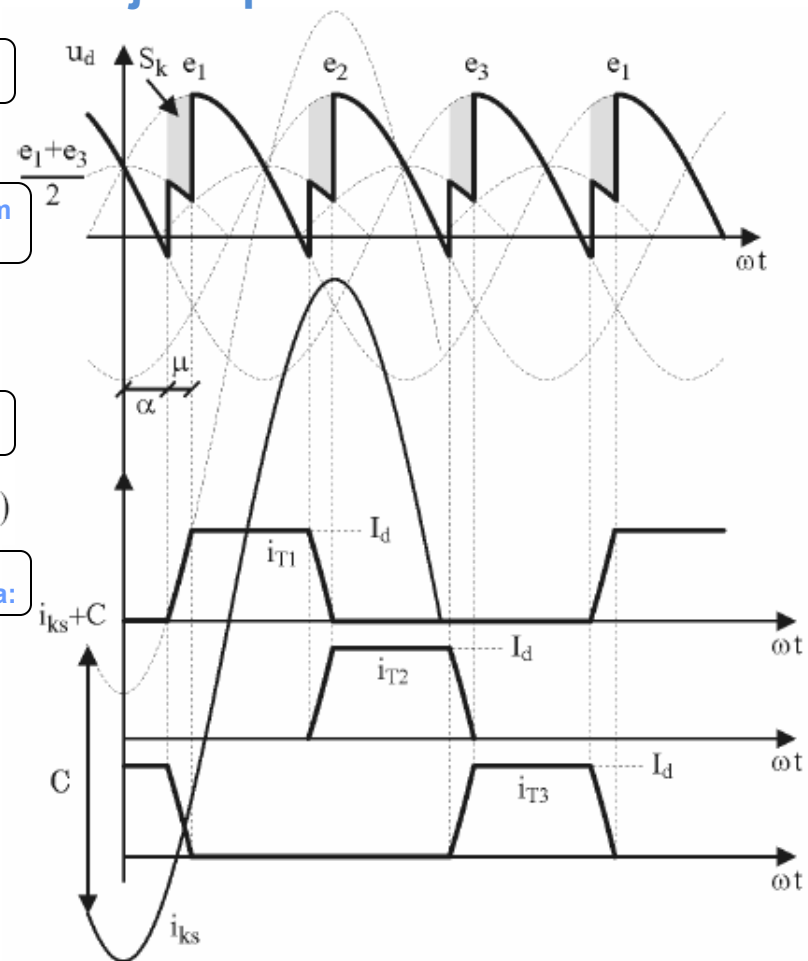
$$i_{T1} = \frac{1}{L_k} \int \frac{\sqrt{6}E}{2} \sin(\omega t) dt + C = -\frac{\sqrt{6}E}{2L_k\omega} \cos(\omega t) + C$$

$$i_{T1}(\alpha) = 0 \Rightarrow C = \frac{\sqrt{6}E}{2X_k} \cos(\alpha) \quad i_{T1} = \frac{\sqrt{6}E}{2X_k} [\cos(\alpha) - \cos(\omega t)]$$

Trenutak završetka komutacije: $\beta = \alpha + \mu$

$$i_{T1}(\beta) = I_d \Rightarrow \cos(\beta) = \cos(\alpha) - \frac{2X_k I_d}{\sqrt{6}E}$$

$$L_k di_{T1} = u_{k1} dt \Rightarrow L_k \Delta I = \int_{\alpha}^{\beta} u_{k1} dt \quad S_k = L_k I_d = \int_{\frac{\alpha}{\omega}}^{\frac{\beta}{\omega}} \frac{1}{2} \sqrt{6}E \sin(\omega t) dt \Rightarrow \cos(\beta) = \cos(\alpha) - \frac{2X_k I_d}{\sqrt{6}E}$$

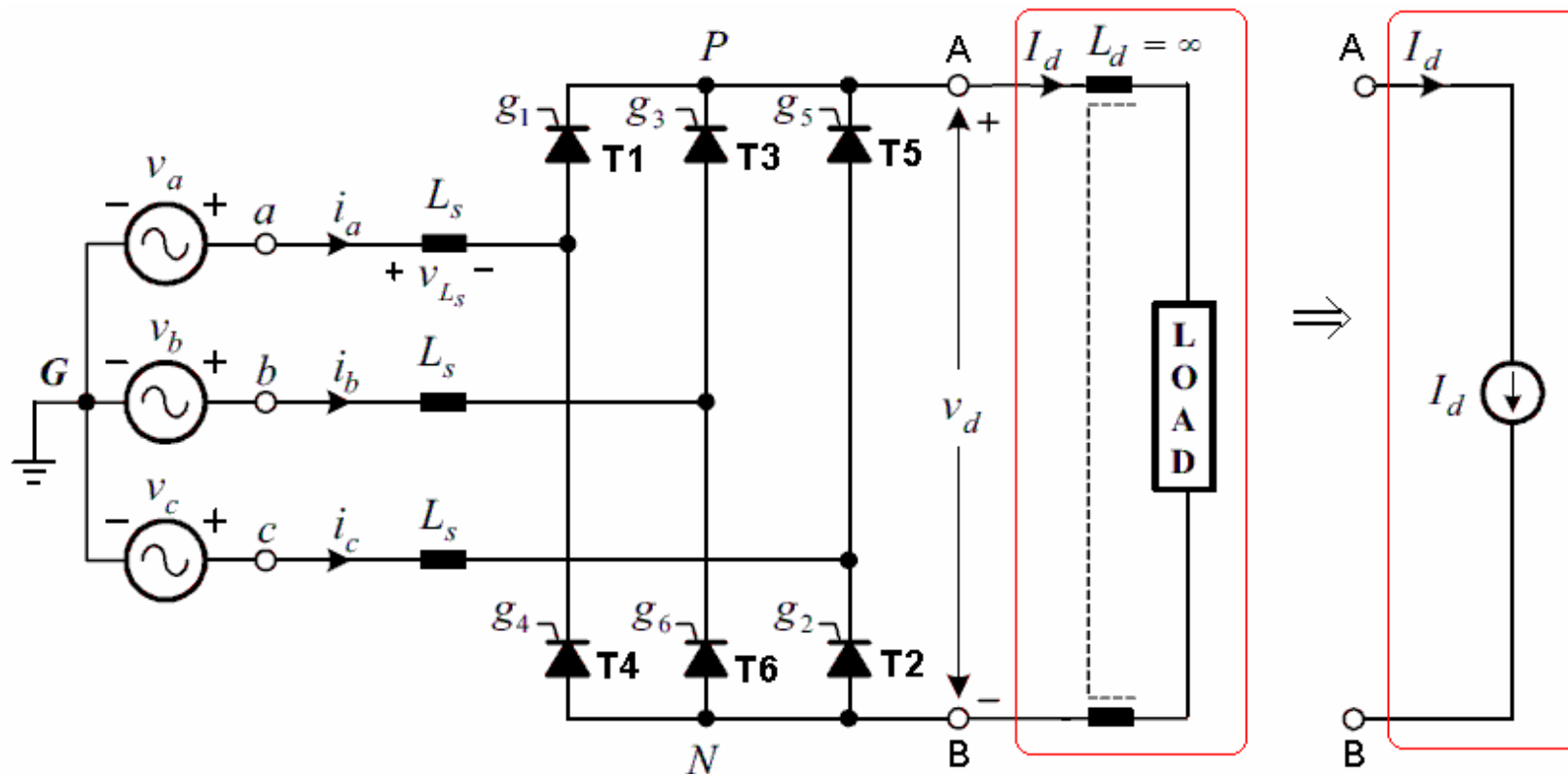


Srednja vrednost izlaznog napona:

$$U_d = \frac{3\sqrt{6}E}{2\pi} \cos(\alpha) - 3 \frac{L_k I_d}{T} = \frac{3\sqrt{6}E}{2\pi} \cos(\alpha) - \frac{3X_k I_d}{2\pi}$$

TROFAZNI MOSNI ISPRAVLJAČ (PUN MOST- 6 TIRISTORA)

TOPOLOGIJA

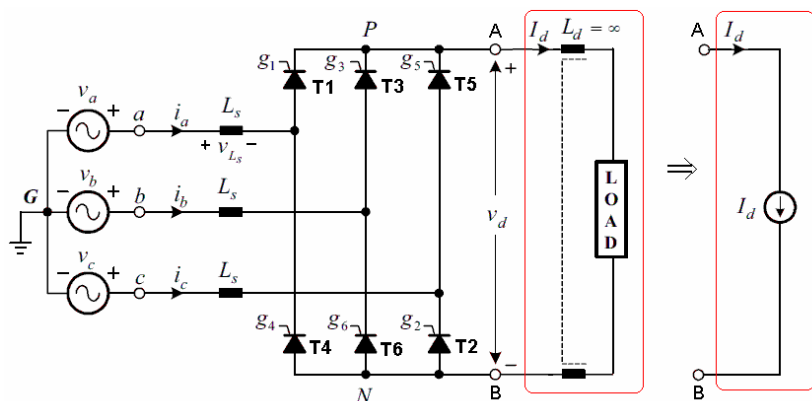


ANALIZA TALASNIH OBLIKA

$$v_a = E\sqrt{2} \cdot \sin \omega t$$

$$v_b = E\sqrt{2} \cdot \sin(\omega t - 120^\circ)$$

$$v_c = E\sqrt{2} \cdot \sin(\omega t - 240^\circ)$$

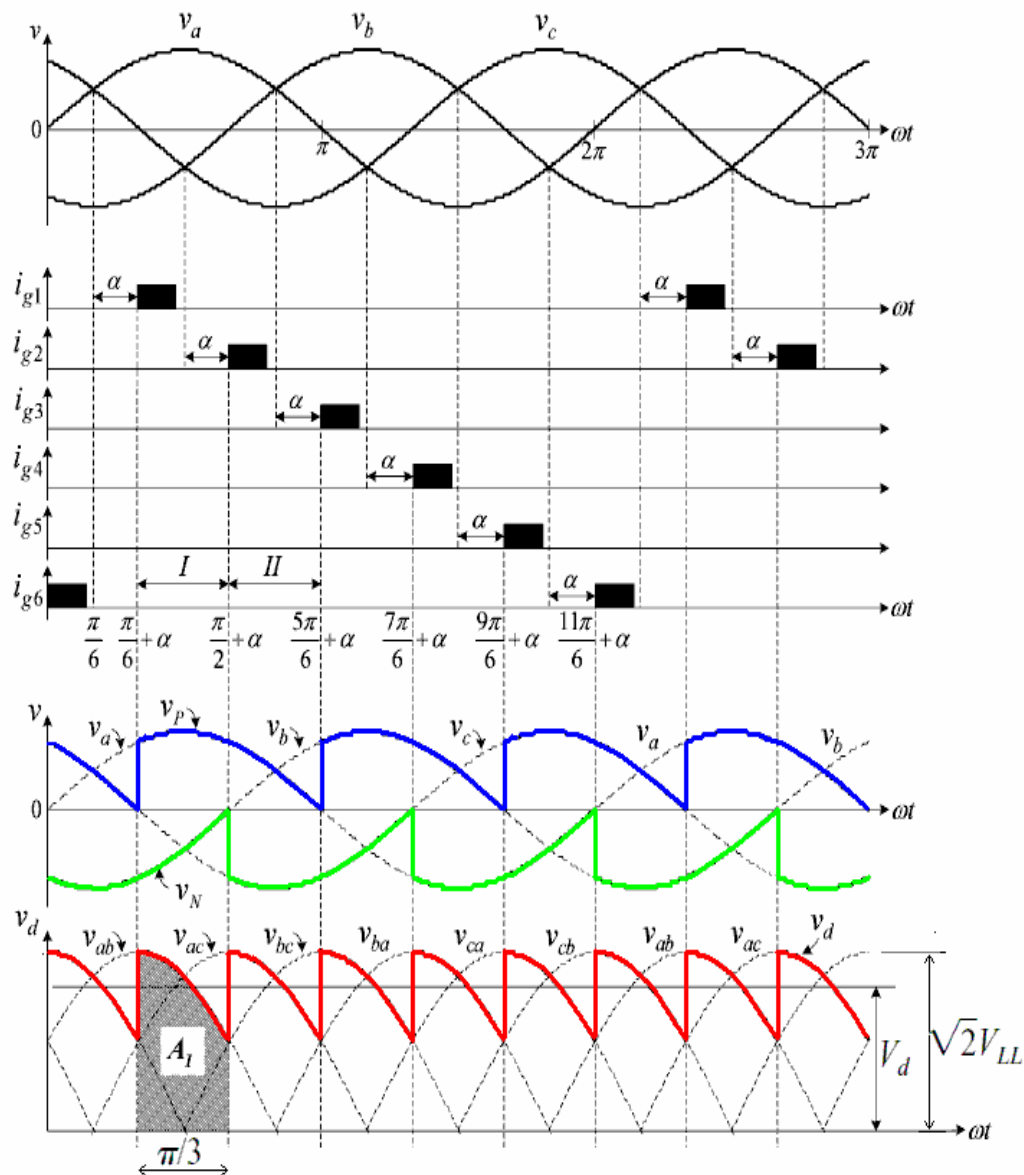


Srednja vrednost izlaznog napona

$$V_d = \frac{3\sqrt{2}}{\pi} \cdot V_{LL} \cdot \cos \alpha$$

$$V_{LL} = \sqrt{3}E$$

$$V_d = \frac{3\sqrt{6}}{\pi} \cdot E \cdot \cos \alpha$$



$$V_d = \frac{\text{POVRŠINA } A_1}{\pi/3} = \frac{1}{\pi/3} \int_{\pi/6+\alpha}^{\pi/2+\alpha} v_{ab} d(\omega t) = \frac{3\sqrt{2}}{\pi} V_{LL} \cos \alpha = 1.35 V_{LL} \cos \alpha$$

$$v_{ab} = \sqrt{2}V_{LL} \sin(\omega t + \pi/6)$$

Spektar linijske struje

Furijeov red viših harmonika:

$$i_a = \frac{2\sqrt{3}}{\pi} I_d \left(\sin(\omega t - \phi_1) - \frac{1}{5} \sin 5(\omega t - \phi_1) - \frac{1}{7} \sin 7(\omega t - \phi_1) + \frac{1}{11} \sin 11(\omega t - \phi_1) \right. \\ \left. + \frac{1}{13} \sin 13(\omega t - \phi_1) - \frac{1}{17} \sin 17(\omega t - \phi_1) - \frac{1}{19} \sin 19(\omega t - \phi_1) + \dots \right)$$

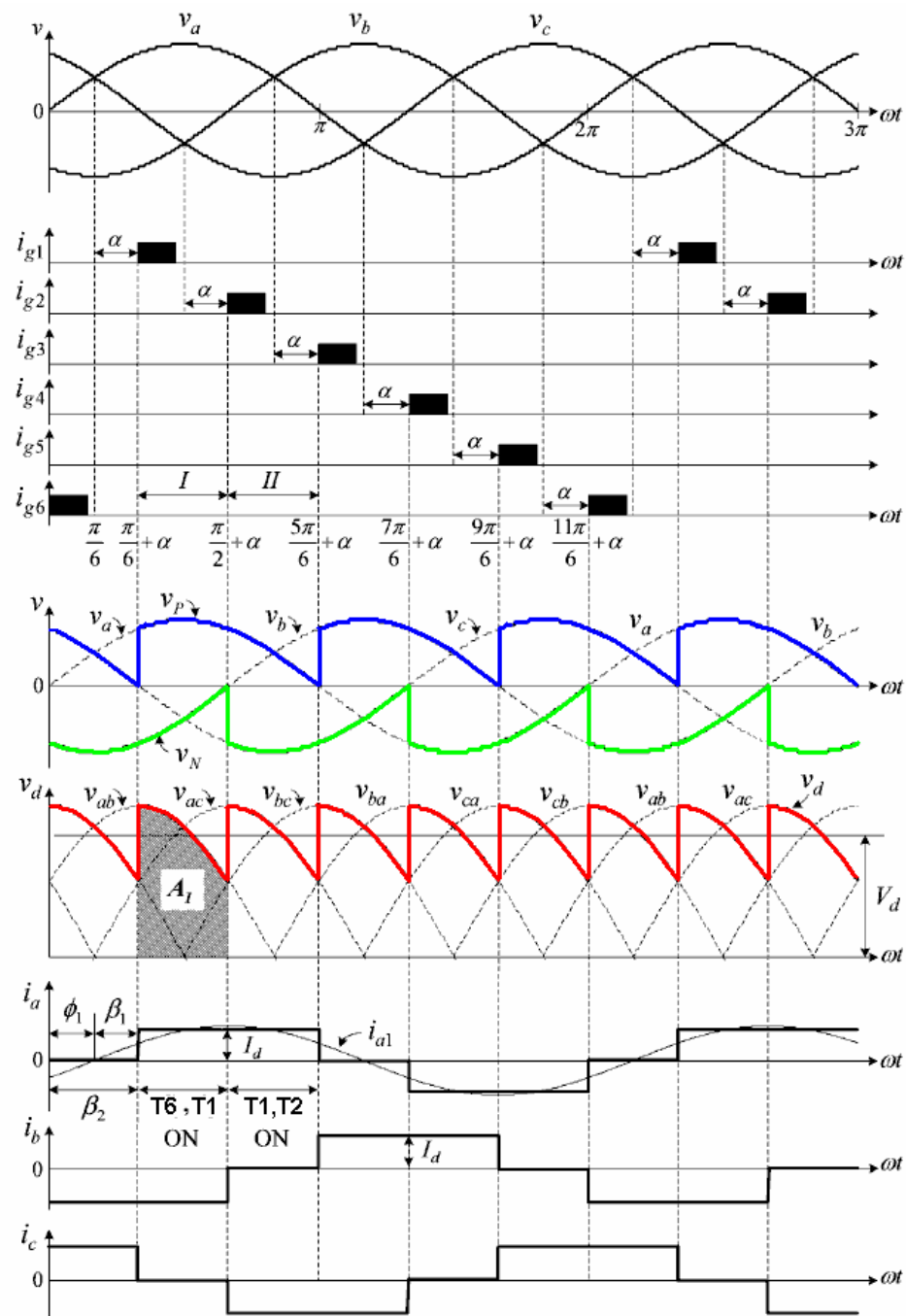
Efektivna vrednost linijske struje:

$$I_a = \left(\frac{1}{2\pi} \int_0^{2\pi} (i_a)^2 d(\omega t) \right)^{1/2} = \left(\frac{1}{2\pi} \left(\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} (I_d)^2 d(\omega t) + \int_{\frac{7\pi}{6}+\alpha}^{\frac{11\pi}{6}+\alpha} (-I_d)^2 d(\omega t) \right) \right)^{1/2} \\ = \sqrt{\frac{2}{3}} I_d = 0.816 I_d$$

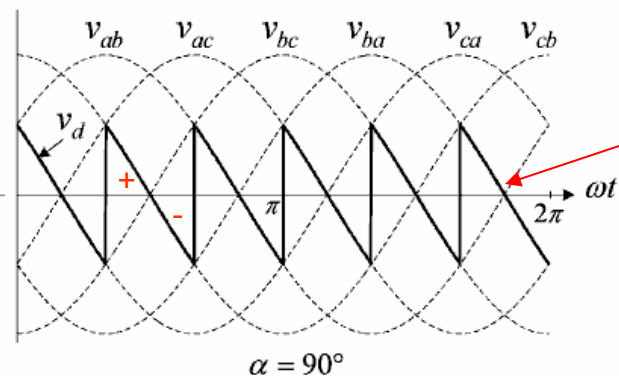
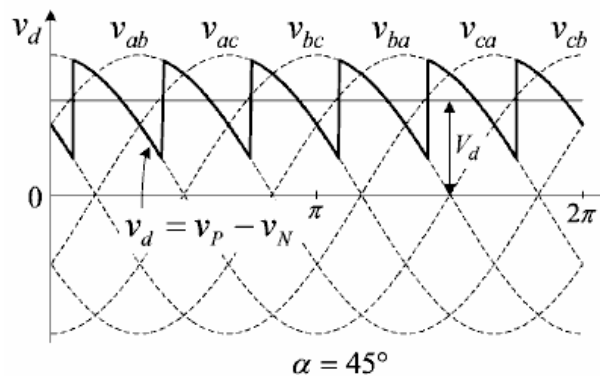
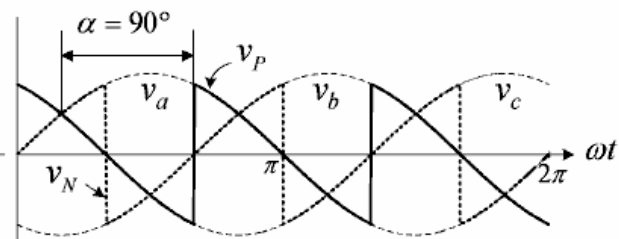
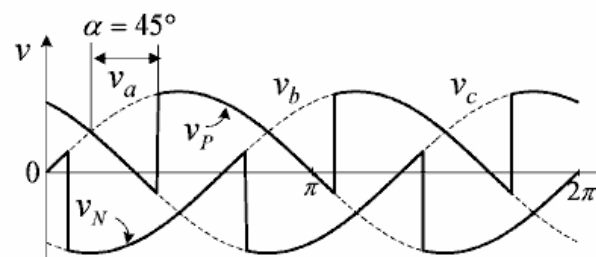
$$I_a = I_b = I_c$$

Ukupno harmonijsko izobličenje:

$$\text{THD} = \frac{\sqrt{I_a^2 - I_{a1}^2}}{I_{a1}} = \frac{\sqrt{(0.816 I_d)^2 - (0.78 I_d)^2}}{0.78 I_d} = 0.311$$



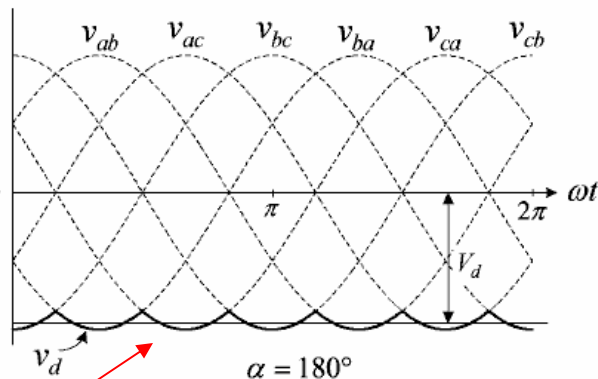
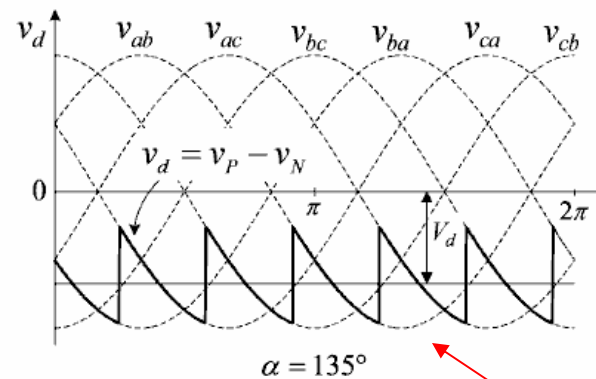
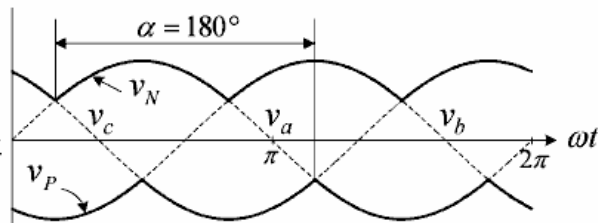
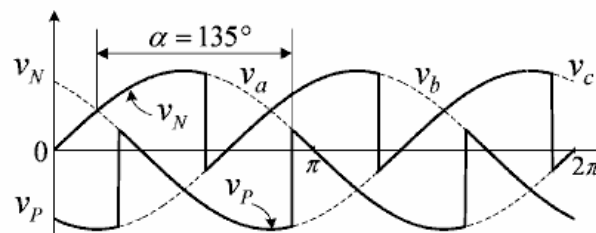
$V_d > 0$ →



$V_d = 0$

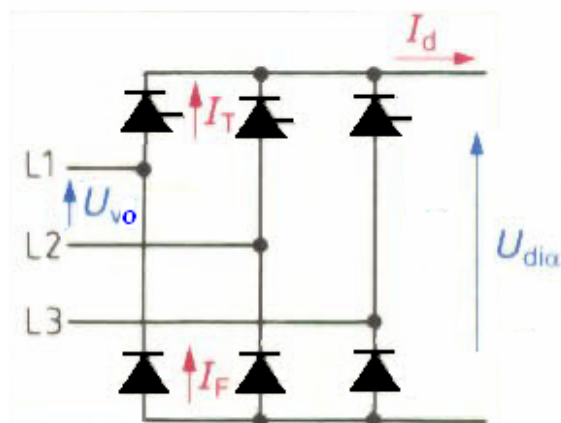
Talasni oblici
izlaznog napona
za različite
vrednosti ugla
upravljanja

α



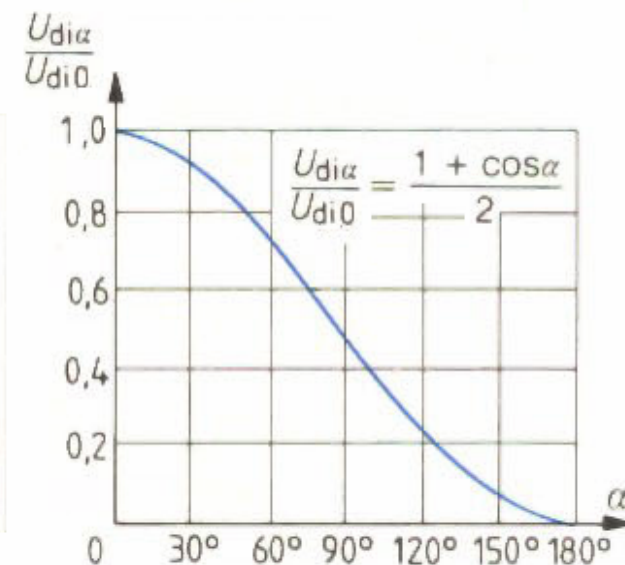
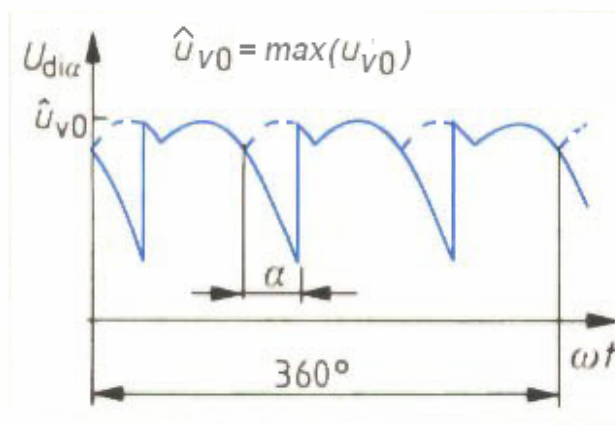
$V_d < 0$

TROFAZNI POLU UPRAVLJIVI ŠESTO - IMPULSNI MOSNI SPOJ



$$U_{dio} = \frac{3\sqrt{2}}{\pi} U_{vo} \quad U_{vo} = \text{RMS}(u_{v0})$$

$$U_{dio} = 1,35 \cdot U_{vo}$$



EFEKAT KOMUTACIONE INDUKTIVNOSTI

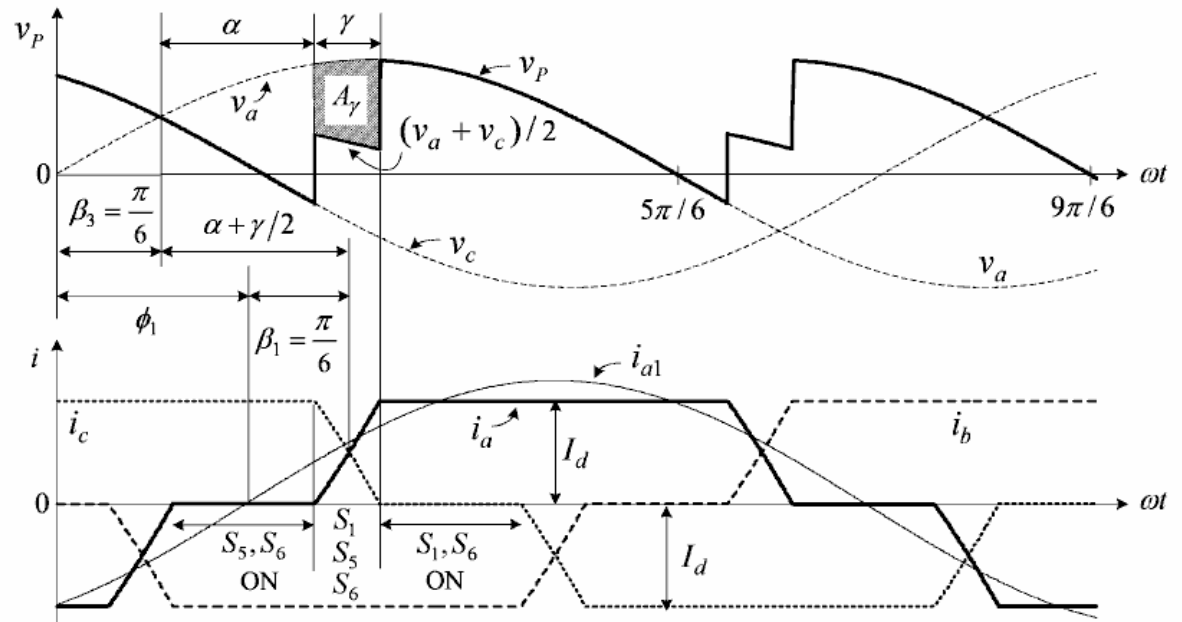
Srednja vrednost izlaznog napona

$$V_d = \frac{3\sqrt{6}}{\pi} \cdot E \cdot \cos \alpha - \frac{3X_k}{\pi} \cdot I_d$$

$$X_k = \omega \cdot L_k$$

$$L_k = L_s$$

$$V_{LL} = \sqrt{3}E$$



$$v_P = -L_s \frac{di_a}{dt} + v_a = -L_s \frac{di_c}{dt} + v_c \quad i_a + i_c = I_d = \text{const} \quad \frac{di_a}{dt} + \frac{di_c}{dt} = 0$$

$$v_P = \frac{v_a + v_c}{2} - \frac{L_s}{2} \left(\frac{di_a}{dt} + \frac{di_c}{dt} \right) \quad v_P = \frac{v_a + v_c}{2}$$

$$A_\gamma = \int_{\frac{\pi}{6} + \alpha}^{\frac{\pi}{6} + \alpha + \gamma} (v_a - v_P) d(\omega t) \quad v_a - v_P = L_s (di_a/dt)$$

$$A_\gamma = \int_0^{I_d} \omega L_s di_a = \omega L_s I_d \quad \Delta V = \frac{A_\gamma}{\pi/3} = \frac{3\omega L_s}{\pi} I_d$$

$$V_d = 1.35 V_{LL} \cos \alpha - \frac{3\omega L_s}{\pi} I_d$$

$$\gamma = \cos^{-1} \left(\cos \alpha - \frac{\sqrt{2}\omega L_s}{V_{LL}} I_d \right) - \alpha$$

POTPUNO UPRAVLJIVI TIRISTORSKI ISPRAVLJAČI-REKAPITULACIJA

Naziv	Spoj	Naponska karakter. kod neisprekidane jednosmerne struje		Karakter. vrednosti ¹⁾		Osobine	Primena
		$\alpha = 60^\circ$ ispravljački pogon	$\alpha = 120^\circ$ invertorski pogon	$\frac{U_{dio}}{U_{vo}}$	$\frac{U_{dix}}{U_{dio}}$		
Dvoimpul-sni mostni spoj B2C				0,90	$\cos \alpha^{2)}$ $\frac{1 + \cos \alpha^{3)}$ 2	• Malo naprezanje ventila usled inverznog napona. • Neznatno povećana konstrukci-ona snaga pret-varačkih transformatora	• Područje snage do oko 10 kW kod neznatnih zahteva u pogledu talasnosti napona
Troimpulsni spoj sa izvedenom nulom M3C				0,68	$\cos \alpha^{2)}$ za $\alpha \leq 30^\circ$: $\cos \alpha^{4)}$ za $30^\circ \leq \alpha \leq 150^\circ$: $0,58 \cdot [1 + \cos (\alpha + 30^\circ)]$	• Isprekidani pogon moguć tek od $\alpha \geq 30^\circ$ • Veliko naprezanje ventila usled inverznog napona. • Zvezdište mora biti potpuno opteretivo	• Pretvaračka sekcija u izvedbi reverzibilnog pretvarača
Dvostruki troimpulsni spoj sa izvedenom nulom M3.2C				0,68	$\cos \alpha^{2)}$	• Isprekidani pogon moguć tek od $\alpha \geq 60^\circ$ • Svi ventili na jednom rashladnom telu. • Dodatni utrošak za usisnu prigušnicu.	• Pretvarači za napone do 300 V. • Upotreba takođe i kod velikih snaga sa većim zahtevima u pogledu talasnosti napona
Šestoim-pulsni mostni spoj B6C				1,35	$\cos \alpha^{2)}$ za $\alpha \leq 60^\circ$: $\cos \alpha^{4)}$ za $60^\circ \leq \alpha \leq 120^\circ$: $\frac{1 + 1,15}{2} \cos (\alpha + 30^\circ)$	• Isprekidani pogon moguć tek od $\alpha \geq 60^\circ$ • Minimalna konstrukci-ona snaga transformatora	• Najvažniji spoj pretvarača za pogone jednosmernom strujom sa nazivnim naponom preko 300 V

¹⁾ za $\alpha = 0^\circ$ važe karakteristike spojeva odgovarajućih neupravljanijh pretvarača ²⁾ kod aktivnog opterećenja i neisprekidane struje ³⁾ kod omskog opterećenja ⁴⁾ nezavisno od opterećenja