(120 min.) DIS - MI - 2016/17

ISTRE:

[5]

1. NAPISATI IZRAZE MATEM. MODELA SMUPM U dq SUSTAVU, OSI, U RELATIVNIM JEDINICAMA (PER UNIT) ZA ELEKTRIČ. VELIČINE $\left(\frac{di_d}{dt} \text{ i } \frac{di_q}{dt}\right)$. BAZNE VRIJEDNOSTI SU:

$$U_B = \sqrt{2}\, U_{fn}, \quad I_B = \sqrt{2}\, I_{fn}, \quad \omega_B = 2\pi f_n = \omega_{el}$$

U_{fn} ↳ eff. vrij. faznog napona; I_{fn} ↳ eff. vrij. fazne struje; f_n ↳ NAZIVNA VRIJEDNOST ELEKTRIČ. BAZNE VRTNJE.

Rj.:

$$(1) \quad \frac{di_d}{dt} = \frac{1}{L_d}\left(u_d - R_s i_d + \omega_e L_q i_q\right)$$

$$(2) \quad \frac{di_q}{dt} = \frac{1}{L_q}\left(u_q - R_s i_q - \omega_e L_d i_d - \omega_e \phi_{mg}\right)$$

$$i_{dPU} = \frac{i_d}{I_B} \quad \Big| \quad L_{dPU} = \frac{L_d}{L_B}; \; L_B = \frac{Z_B}{\omega_B} \quad \Big| \quad R_{sPU} = \frac{R_s}{Z_B}$$

$$\omega_{ePU} = \frac{\omega_e}{\omega_B} \quad \Big| \quad \phi_{mgPU} = \frac{\phi_{mg}}{\phi_B}; \; \phi_B = \frac{U_B}{\omega_B} \quad \Big| \quad u_{DPU} = \frac{u_D}{U_B}$$

$$(1) \quad I_B \cdot \frac{di_{dPU}}{dt} = \frac{\omega_B}{Z_B \cdot L_{DPU}}\left[u_{dPU} \cdot U_B - R_{sPU} \cdot Z_B \cdot i_{DPU} \cdot I_B + \omega_{ePU} \cdot \omega_B \cdot L_{qPU} \cdot \frac{Z_B}{\omega_B} \cdot i_{qPU} \cdot I_B\right]$$

$$\frac{di_{DPU}}{dt} = \frac{\omega_B}{Z_B L_{DPU}}\left[u_{DPU} \cdot Z_B - i_{DPU} R_{sPU} \cdot Z_B + \omega_{ePU} L_{qPU}\, i_{qPU} \cdot Z_B\right]$$

$$\frac{di_{DPU}}{dt} = \frac{\omega_B}{L_{DPU}}\left[u_{DPU} - i_{DPU} R_{sPU} + \omega_{ePU} \cdot L_{qPU} \cdot i_{qPU}\right]$$

$$(2)\quad \frac{di_q}{dt} = \frac{1}{L_q}\left(u_q - R_s i_q - \omega_e L_d i_d - \omega_e \phi_{mg}\right)$$

$$I_B \cdot \frac{di_{qPU}}{dt} = \frac{\omega_B}{Z_B L_{qPU}}\Big[U_B u_{qPU} - Z_B R_{sPU} \cdot i_{qPU} \cdot I_B -$$

$$- \omega_B \cdot \omega_{ePU} \cdot \frac{Z_B}{\omega_B} \cdot L_{DPU} \cdot I_B \cdot i_{dPU} - \omega_B \cdot \omega_{ePU} \cdot \frac{U_B}{\omega_B} \cdot \phi_{mgPU}\Big]$$

$$\frac{di_{qPU}}{dt} = \frac{\omega_B}{L_{qPU}}\left[u_{qPU} - R_{sPU} i_{qPU} - \omega_{ePU} L_{dPU} i_{dPU} - \omega_{ePU} \phi_{mgPU}\right]$$

VERZIJA KOJA BI SE MOGLA POJAVITI NA ISPITU:

ODREDI $\frac{d\omega_m}{dt}$ U P.U., SMUPM:

RJ.:

$$(3)\quad J_m \frac{d\omega_m}{dt} = \underbrace{M_{em}}_{= \frac{3}{2} p \left[\phi_{mg} i_q + \underbrace{(L_d - L_q) i_d i_q}_{=0 \text{ ZA SMVPM}}\right] \text{ ZA SMUPM}} - D\omega_m - M_t$$

$$J_m \omega_{mB} \frac{d\omega_{mPU}}{dt} = M_B M_{emPU} - D_B D_{PU} \cdot \omega_{mB} \omega_{mPU} - M_B M_{tPU}$$

$$J_m \omega_{mB} \frac{d\omega_{mPU}}{dt} = M_B M_{emPU} - \frac{M_B}{\omega_B} \cdot \frac{\omega_B}{p} \cdot D_{PU} \omega_{mPU} - M_B M_{tPU}$$

$$\frac{d\omega_{mPU}}{dt} = \underbrace{\frac{M_B}{J_m \omega_{mB}}}_{= 1/T_m}\left[M_{emPU} - \frac{D_{PU}\,\omega_{mPU}}{p} - M_{tPU}\right]$$

$\frac{d\omega_{ePU}}{dt} \rightarrow$ SAMO SE POMNOŽI DESNA S "p"

[5]

2) SINKRONI STROJ S PERMAN. MAGN. IMA SLJ. PARAMETRE:

$p = 2$ (BROJ PARI POLOVA), $L_d = 7 \cdot 10^{-3}$ H (INDUKTIVITET U d OSI),

$L_q = 7 \cdot 10^{-3}$ H (IND. U q OSI), $R_s = 2.98\ \Omega$ (OTPOR STATORA),

$\phi_{mg} = 0.125$ Wb (MAGN. TOK PERMAN. MAGN.), $J_m = 0.47 \cdot 10^{-4}$ kgm^2 (MOMENT INERCIJE),

$D = 1.1 \cdot 10^{-4}$ Nms (FAKTOR PRIGUŠENJA).

ODREDITI POJAČANJE REGULATORA STRUJE i_q AKO JE STAC. POJAČANJE ZATVORENOG KRUGA: (a) $\alpha = 0.4$

P tip!

(b) $\alpha = 0.9$

Rj: $L_d = L_q \Rightarrow$ SMVPM!

$$\frac{di_q}{dt} = \frac{1}{L_q}\left(u_q - R_s i_q - \omega_e L_d i_d - \omega_e \phi_{mg}\right)$$

SUPST.: $\hat{U}_q = U_q - \Omega_e L_d I_d - \Omega_e \phi_{mg}$

$$sI_q = \frac{1}{L_q}\hat{U}_q - \frac{R_s}{L_q} I_q$$

P tip:

$$\frac{I_q}{\hat{U}_q} = \frac{\frac{1}{L_q}}{s + R_s/L_q} \quad ; \quad \hat{U}_q = k_c^q\left(I_q^* - I_q\right)$$

$$sI_q = \frac{k_c^q}{L_q}\left(I_q^* - I_q\right) - \frac{R_s}{L_q} I_q$$

$$\frac{I_q}{I_q^*} = \frac{k_c^q / L_q}{s + \frac{k_c + R_s}{L_q}}$$

$$\frac{I_q}{I_q^*} = \frac{k_c^2 \cancel{N}}{sL_q + k_c^2 + R_s}$$

$$\alpha = ? \Rightarrow \alpha = \lim_{s\to 0} sI_q \Bigg|_{I_q^* = \frac{1}{s}} = \frac{k_c^2}{k_c^2 + R_s}$$

$$k_c^2 = k_c^2 \alpha + R_s \alpha$$

$$k_c^2 = \frac{R_s \alpha}{(1-\alpha)}$$

(a) $\alpha = 0.4 \Rightarrow k_c^2 = 1.99$

(b) $\alpha = 0.9 \Rightarrow k_c^2 = 26.82$ //

3. [6]

ODREDI IZRAZE ZA PARAMETRE PID reg. POZICIJE (k_c, τ_I, τ_D) SMVPM. PRIJ. FJA PID reg. JE $C(s) = k_c\left(1 + \frac{1}{\tau_I s} + \tau_D s\right)$. REGULATOR STRUJE i_q JE P TIPA (KAO U ZAD. 2.)

RJ.: $\vartheta_e = \frac{1}{s}\Omega_e$ SMVPM ($L_d = L_q$)!

$$s\Omega_e = \frac{p}{J_m}\left\{\frac{3}{2}p\left[\phi_{mg} I_q + \underbrace{(L_d - L_q) I_d I_q}_{\text{SMVPM} \Rightarrow 0}\right] - \frac{D}{p}\Omega_e - \underbrace{M_t}_{=0}\right\}$$

$$s\Omega_e = \frac{p^2}{J_m} \cdot \frac{3}{2}\phi_{mg} I_q - \frac{D}{J_m}\Omega_e$$

$$\frac{\Omega_e}{I_q} = \underbrace{\frac{\frac{3}{2}\frac{p^2}{J_m}\phi_{mg}}{s+\frac{D}{J_m}}}_{X}$$

$$k_c^q = \frac{R_s\alpha}{1-\alpha}$$

$$\frac{I_q}{I_q^*} \text{ iz 2. ZAD} \Rightarrow \frac{k_c^q}{sL_q + k_c^q + R_s}$$

$$\frac{\Omega_e}{I_q^*} = X \cdot \frac{\frac{R_s\alpha}{1-\alpha}}{\frac{sL_q(1-\alpha)+R_s\alpha+R_s(1-\alpha)}{1-\alpha}}$$

$$\frac{\Omega_e}{I_q^*} = X\cdot \frac{R_s\alpha}{sL_q(1-\alpha)+R_s} = \frac{\frac{3}{2}\frac{p^2}{D}\phi_{mg}}{\frac{J_m}{D}s+1}\cdot\frac{R_s\alpha}{\underbrace{sL_q(1-\alpha)}_{\ll \frac{J_m}{D}s}+R_s}$$

$$\frac{\Theta_e}{I_q^*} = \frac{\overbrace{\frac{3}{2}\frac{p^2}{J_m}\phi_{mg}\alpha}^{\to b}}{s\left(s+\underbrace{\frac{D}{J_m}}_{\to a}\right)} \qquad \frac{b}{s+a}$$

$$C(s) = k_c^\theta\left(1+\frac{1}{t_i^\theta s}+t_D^\theta s\right) \quad ; \quad G(s) = \frac{b}{(s+a)s}$$

ZATV. KRUG (PID): $\frac{C(s)G(s)}{1+C(s)G(s)} = \dfrac{\frac{k_c^\theta s + k_c^\theta/t_i^\theta + k_c^\theta t_D^\theta s^2}{s^2(s+a)}}{\frac{s^3+s^2a+k_c^\theta s b + \left(\frac{k_c^\theta}{t_i^\theta}\right)b + s^2 k_c^\theta t_D^\theta b}{s^2(s+a)}}$

JER JE 2. RED

$$\frac{Y(s)}{R(s)} = \frac{\Theta_e}{\Theta_e^*} = \frac{k_c^\theta s + k_c^\theta/t_i^\theta + s^2 k_c^\theta t_D^\theta}{s^3+s^2(a+k_c^\theta t_D^\theta b)+s(k_c^\theta b)+\frac{k_c^\theta b}{t_i}}$$

$$\underbrace{(s^2+2\xi\omega_n s+\omega_n^2)(s+n\omega_n)}_{y}= \,=\underbrace{s^3+s^2(a+K_c^\theta \tau_D^\theta b)+s(K_c^\theta b)+\frac{K_c^\theta b}{\tau_i^\theta}}_{x}$$

$$s^3+s^2(n\omega_n+2\xi\omega_n)+s(2\xi n\omega_n^2+\omega_n^2)+n\omega_n^3=y$$

1 2 3

$$y=x$$

$$\Downarrow$$

2 $\boxed{K_c^\theta=\frac{2\xi n\omega_n^2+\omega_n^2}{b}}$ $\quad a=D/J_m$

UZ &

$$b=\frac{3}{2}\frac{p^2\psi_{mg}d}{J_m}$$ //

3 $\boxed{\tau_i^\theta=\frac{2\xi n+1}{n\omega_n}}$

1 $a+K_c^\theta\tau_D^\theta b=n\omega_n+2\xi\omega_n \Rightarrow \boxed{\tau_D^\theta=\frac{\omega_n(2\xi+n)-a}{2\xi n\omega_n^2+\omega_n^2}}$

4 [4]

SMPM (PARAMETRI IZ ZAD. 2) RADI U REGULACIJI MOMENTA. REG. STRUJE JE P TIPA S POJAČANJEM $K_c^q=10R_s$. ODREDITI STATIČKU GREŠKU (ODSTUPANJE STVARNE OD ŽELJENE VRIJ. U STAC. STANJU) STRUJE i_q NA SKOKOVITU PROMJENU POSTAVLJENE VELIČINE MOMENTA, M_{om}^* S ~~0~~ NA 1 Nm!

SMVPM! $L_d=L_q$

$$\frac{E}{I_q^*} = \frac{I_q^* - I_q}{I_q^*} \quad ; \quad sI_q = \frac{\hat{U}_q}{L_q} - \frac{R_s}{L_q} I_q$$

$$sI_q = \frac{K_c^q}{L_q}(I_q^* - I_q) - \frac{R_s}{L_q} I_q$$

$$\frac{E}{I_q^*} = 1 - \frac{I_q}{I_q^*}$$

$$\frac{I_q}{I_q^*} = \frac{K_c/L_q}{s + \frac{K_c^q}{L_q} + \frac{R_s}{L_q}} = \frac{K_c^q}{sL_q + K_c^q + R_s}$$

$$\frac{E}{I_q^*} = 1 - \frac{K_c^q}{sL_q + K_c^q + R_s}$$

$$\frac{E}{I_q^*} = \frac{sL_q + R_s}{sL_q + K_c^q + R_s} \quad ; \quad M_{em} = \frac{3}{2} p \Big[\phi_{mg} i_q + \underbrace{(L_d - L_q) i_d i_q}_{=\cancel{0}}\Big]$$

SMVPM

A I KOD SMVPM

JER SE i_d^* POSTAVI U $\cancel{0}$

$$I_q^* = \frac{2 M_{em}^*}{3 p \phi_{mg}} \quad \text{uz} \quad M_{em}^* = \frac{1}{s}$$

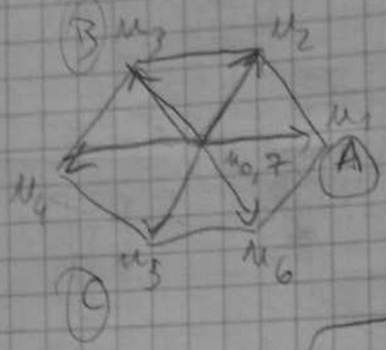
(SKOKOVITA FJA $0 \to 1$)

$$E = \frac{sL_q + R_s}{sL_q + K_c^q + R_s} \cdot \frac{2}{3 p s \phi_{mg}}$$

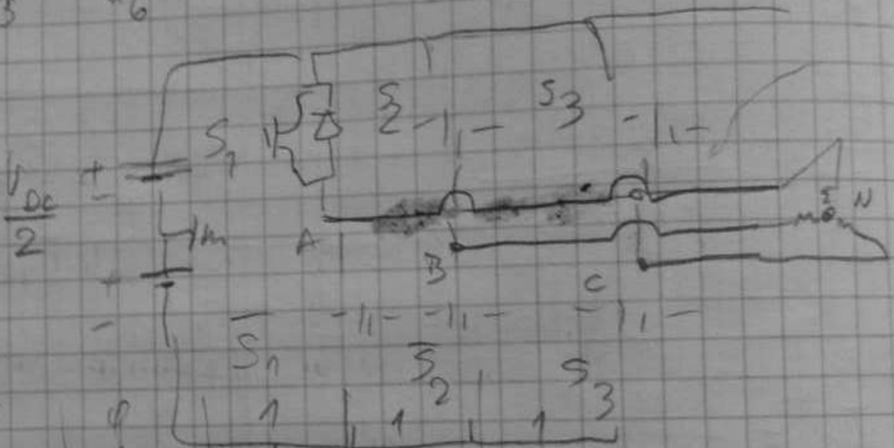
$$\lim_{t \to \infty} e(t) = \lim_{s \to 0} sE(s) = \frac{R_s}{K_c^q + R_s} \cdot \frac{2}{3 p \phi_{mg}} = \frac{\cancel{R_s}}{11 \cancel{R_s}} \cdot \frac{2}{3 p \phi_{mg}} = 0.2424$$

5. [3] NAVESTI OSNOVNE RAZLIKE MODULACIJE SIX STEP, SINUSNE I VEKTORSKE PWM KOD PRETVARAČA NAPONA I FREKVENCIJE ZA DOBIVANJE ŽELJENE AMPLITUDE I FREKV. NAPONA NA STEZALJKAMA STROJA

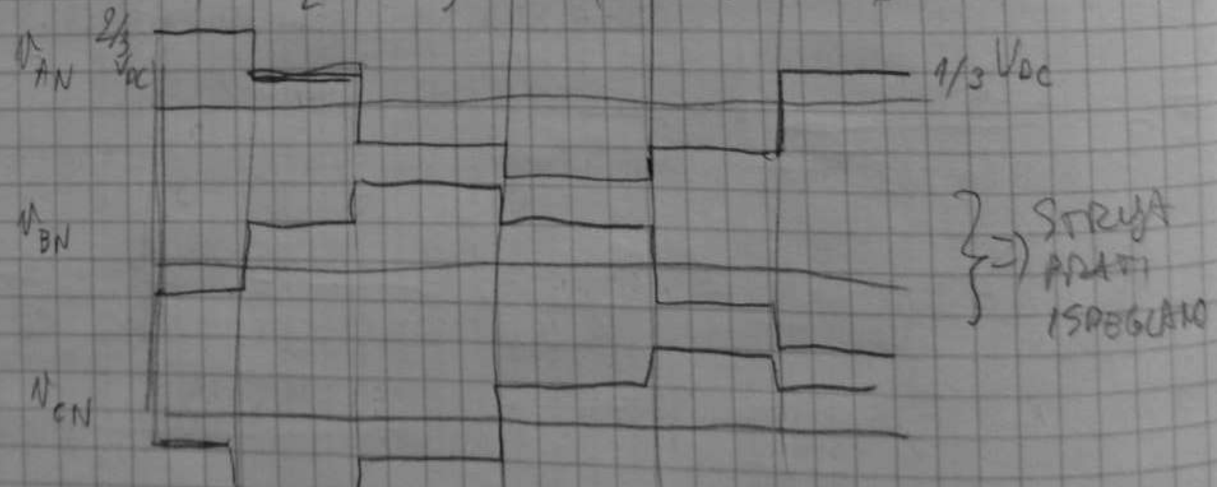
SIX STEP:



	u_0							u_7
S_1	0	0	0	0	1	1	1	1
S_2	0	0	1	1	1	0	0	1
S_3	0	1	1	0	0	0	1	1



	U_1	U_2	U_3	U_4	U_5	U_6
C	0	0	0	1	1	1
B	0	1	1	1	0	0
A	1	1	0	0	0	1



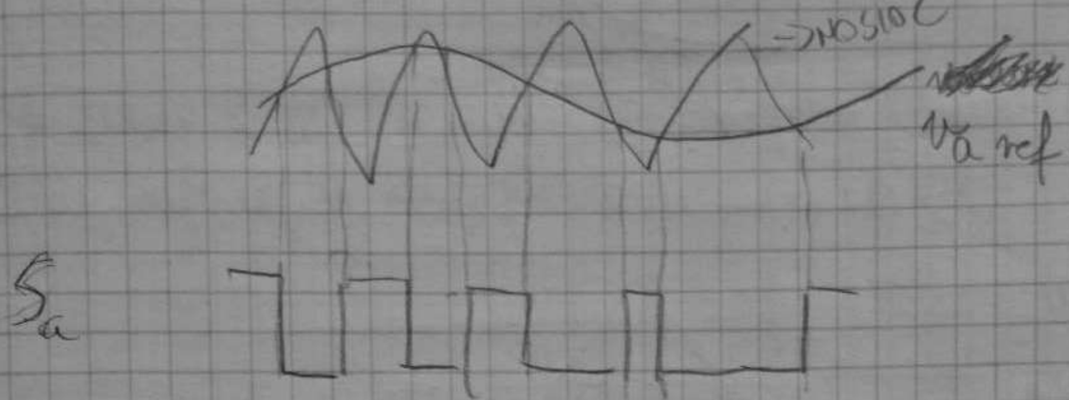
→ NIJE PWM, DEFINIRA SAMO frekv. osnovnog harmonika (ovisno o ω_e), NE MOŽE MIJENJATI AMPLITUDU (TREBALO BI MIJENJATI V_{DC}), MAX. AMPL. $\frac{2}{\pi}V_{DC}$

→ JEDNOSTAVNA, MALI GUBICI, ALI LOŠ HARMONIJSKI SASTAV (NEMA 3. HARM. & VIŠEHAR

SINUSNA PWM -> MIJENJA AMPL. & frekv.

REFERENTNI ∿ } USPOREDBA
NOSIOC ∿∿ }

∿ > ∿∿ => IZLAZ JE FAZE ($S_{1,4,2} = 1$)



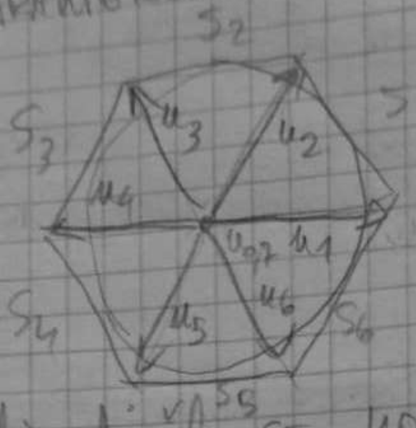
-> veći gubici zbog bržeg sklapanja, bolji spektar, u linearnom području rada ($m_a = \frac{U_0}{U_{DC}/2} < 1$) IZLAZ PROPORCIONALAN REFERENCI

-> INJEKTIRA SE ZERO-SEQUENCE ($\frac{1}{6} m_m \sin(3\omega_e t)$), DODAJE
1/4 ~> SMANJUJE I THD
REFERENTNOM DA BI SE POVEĆAO LINEARNI RASPON MODULACIJE
(& NE BILO OGRANIČENO NA $U_{DC}/2$)

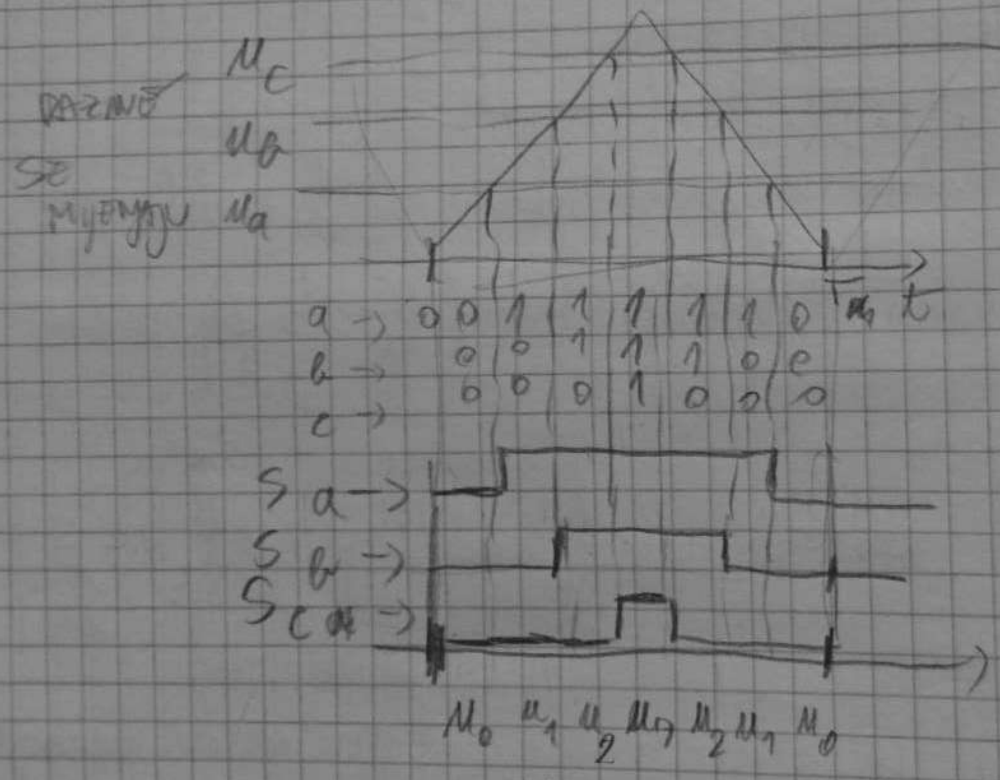
f_{nn} -> neparni višekratnik referentne frekv. DA SE SMANJI UTJECAJ VIŠIH HARMONIKA

VEKTORSKA PWM (SVPWM)

→ ovo o 2 KARAKTERIST. vektora OVISNO O SEKTORU



→ vremenski odsječak SE KORISTI S 2 VEKTORA & 2 NULTA, NPR $S_1 \to u_1, u_2, u_0, u_7$

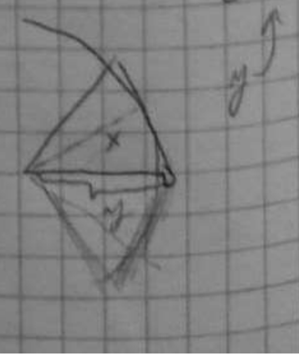


→ SEKTOR 1

→ MAX. AMPLITUDA $\frac{V_{DC}}{\sqrt{3}}$, jer su maximumi kar. vektora $\frac{2}{3}V_{DC}$

x

y



6. [3] ODREDI UKUPNO STATORSKO PROTJECANJE $F(t)^{\theta}$ ZA POLOŽAJ $\theta = 90^{\circ}$ U TRENUTKU $t = 1\,s$, AKO JE:

$$i_a(t) = 5\cos(314t)$$

$$i_b(t) = 5\cos\left(314t - \frac{2\pi}{3}\right)$$

$$i_c(t) = 5\cos\left(314t - \frac{4\pi}{3}\right).$$

BROJ ZAVOJA PO POJEDINOJ FAZI JE

$$N_1 = N_2 = N_3 = N_s = 100$$

$$F_a(t) = N_s \cdot I_s \cdot \cos(314t) = 500\cos(314t)$$

$$F_b(t) = 500\cos(314t - 2\pi/3)$$

$$F_c(t) = 500\cos(314t - 4\pi/3)$$

$$F_a(t)^{\theta} = F_a(t)\cos(0^{\circ} - \theta)$$

$$F_b(t)^{\theta} = F_b(t)\cos\left(\frac{2\pi}{3} - \theta\right)$$

$$F_c(t)^{\theta} = F_c(t)\cos\left(\frac{4\pi}{3} - \theta\right)$$

$$F(t)^{\theta} = \frac{3}{2}\,\mathrm{Re}\,\underbrace{\left\{\frac{2}{3}\left[F_a(t) + F_b(t)e^{j2\pi/3} + F_c(t)e^{j4\pi/3}\right]e^{-j\theta}\right\}}_{\vec{F}(t)}$$

PROSTORNI VEKTOR PROTJ.

...

$$F(t)^{\theta} = \frac{3}{2} F_m \cos(\omega t + \phi_0 - \theta)$$

$$\phi_0 = 0^{\circ} \qquad \theta = 90^{\circ}$$

$$F(t)^{\theta} = \frac{3}{2} \cdot 500 \cos(314 - 90^{\circ}) = \frac{3}{2} \cdot 500 \cdot \sin(314) = -118.95$$

AMPER ZAVOJA

7. [4] ZA SUSTAV UPRAVLJANJA BRZINOM VRTNJE SINKRONOG MOTORA S UNUTARNJIM PERM. MAGN. NAPISATI IZRAZE ZA UPRAVLJAČKE SIGNALE u_d i u_q (U VREM. DOMENI) IZ REGULATORA STRUJA i_d i i_q (UZETI U OBZIR RASPREZANJE). ZA DOBIVENE IZRAZE ZA U_d i U_q NACRTATI BLOKOVSKU SHEMU. ODABRATI TIP REGULATORA STRUJE i_d, odnosno i_q TAKAV DA JE STATIČKA GREŠKA (ODSTUPANJE STVARNE OD ŽELJENE VRTNJE U STAC. STANJU) BRZINE VRTNJE STROJA JEDNAKA NULI.

SMUPM

$$\frac{di_d}{dt} = \frac{1}{L_d}\left(u_d - R_s i_d + L_q \omega_e i_q\right)$$

$$\frac{di_q}{dt} = \frac{1}{L_q}\left(u_q - R_s i_q - L_d \omega_e i_d - \omega_e \Phi_{mg}\right)$$

IZLAZI IZ REG.

$$\hat{U}_d = U_d + L_q \omega_e i_q$$

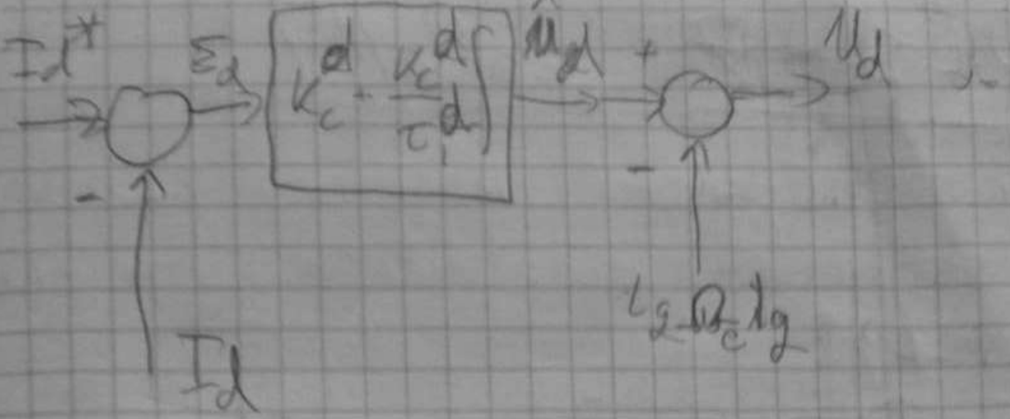
$$\hat{U}_q = U_q - L_d \omega_e i_d - \omega_e \Phi_{mg}$$

PI $\quad \hat{U}_d = K_c^d\left(i_d^*(t) - i_d(t)\right) + \frac{K_c^d}{T_i^d}\int_0^t \left(i_d^*(\tau) - i_d(\tau)\right) d\tau$

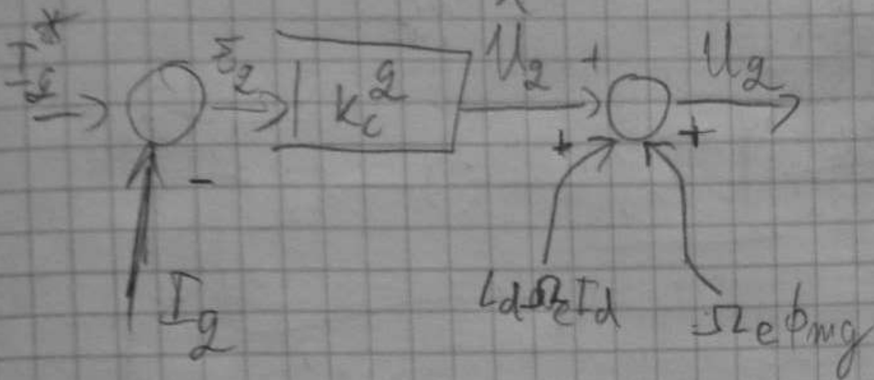
P (MOŽE I PI) $\quad \hat{u}_q = K_c^q\left(i_q^*(t) - i_d(t)\right)$

→ NADREĐENI REGULATOR (BRZINE ω_e) MORA BITI PI TIPA DA STATIČKA GREŠKA = 0

U_d :



U_q :



EKRIZ:

(1) $$U_d = \hat{U}_d - L_q \Omega_e I_q$$

$$u_d(t) = \hat{u}_d(t) - L_q \omega_e(t) i_q(t)$$

$$= L_d \frac{di_d(t)}{dt} + R_s i_d(t) - L_q \omega_e(t) i_q(t)$$

(2) $$u_q(t) = \hat{u}_q(t) + L_d \omega_e(t) i_d(t) + \omega_e(t) \phi_{mg}$$

$$u_q(t) = \frac{di_q(t)}{dt} \cdot L_q + R_s i_q(t) + L_d \omega_e(t) i_d(t) + \omega_e(t) \phi_{mg}$$