

# Regulisani elektromotorni pogoni sa mašinama za jednosmernu struju

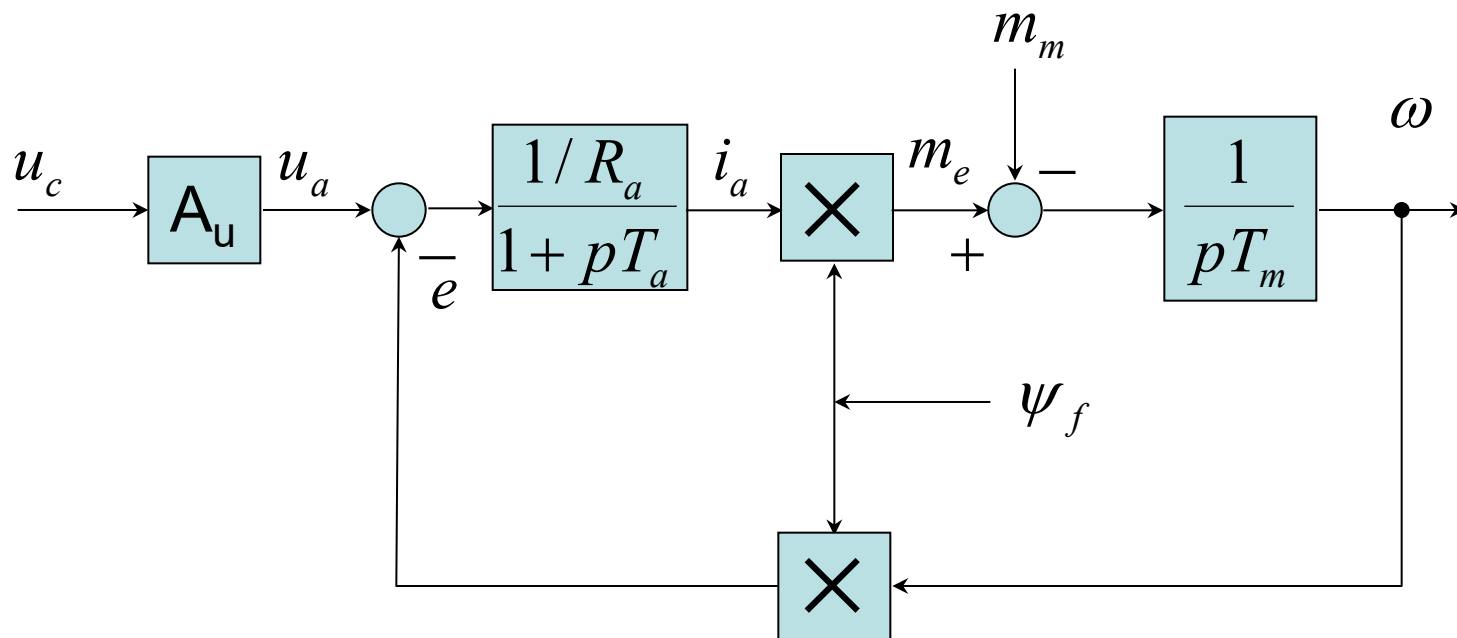
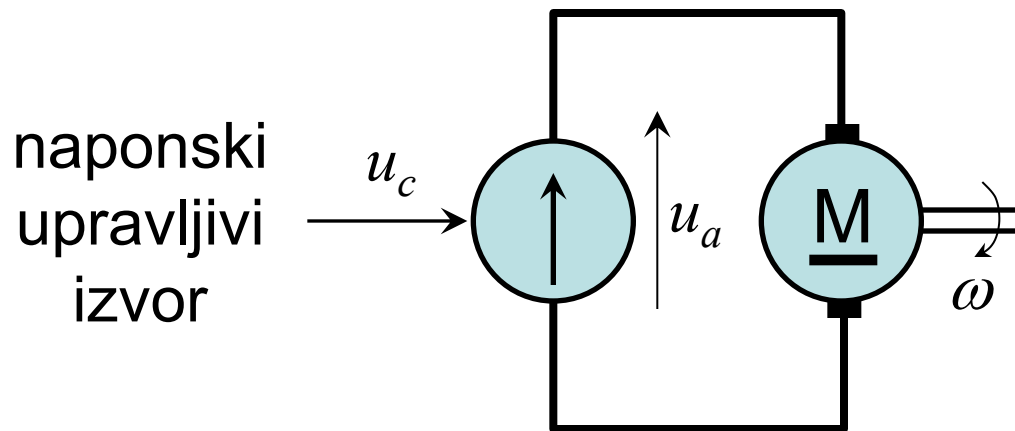
Osnovne karakteristike

Načini realizacije (aktuatora)

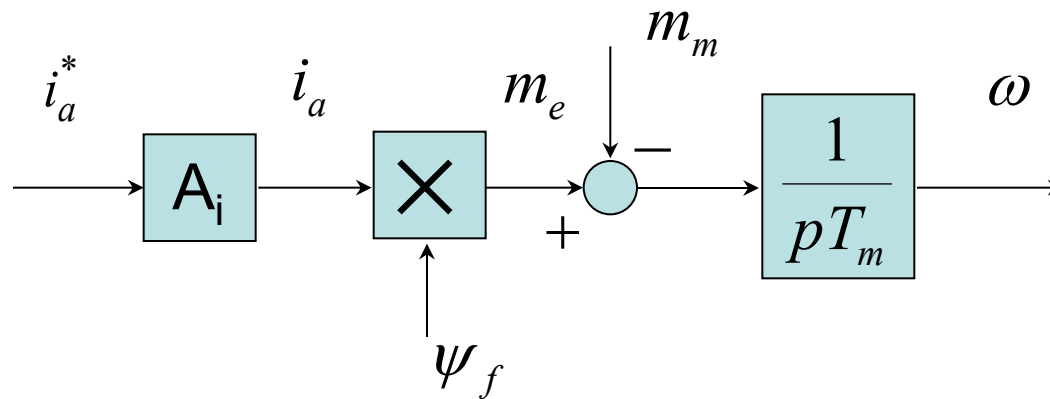
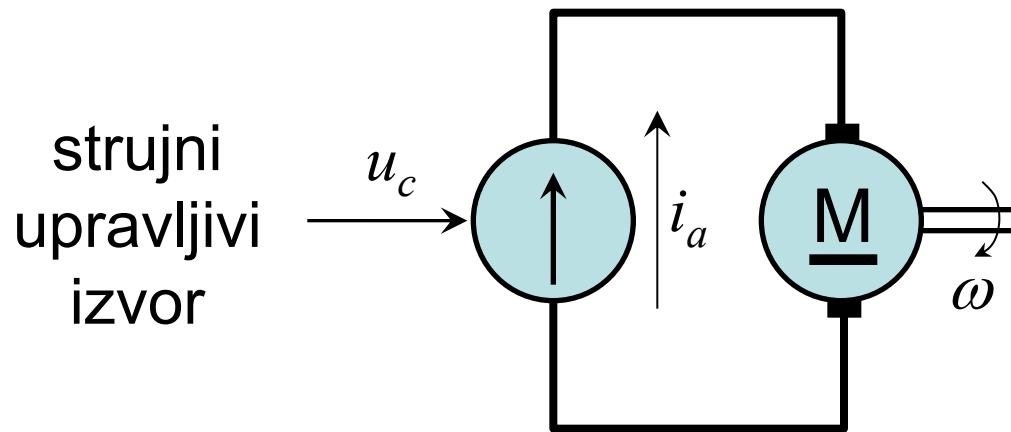
Rad u 2 ili 4 kvadranta

Rad u proširenom opsegu brzina

# Naponski izvor



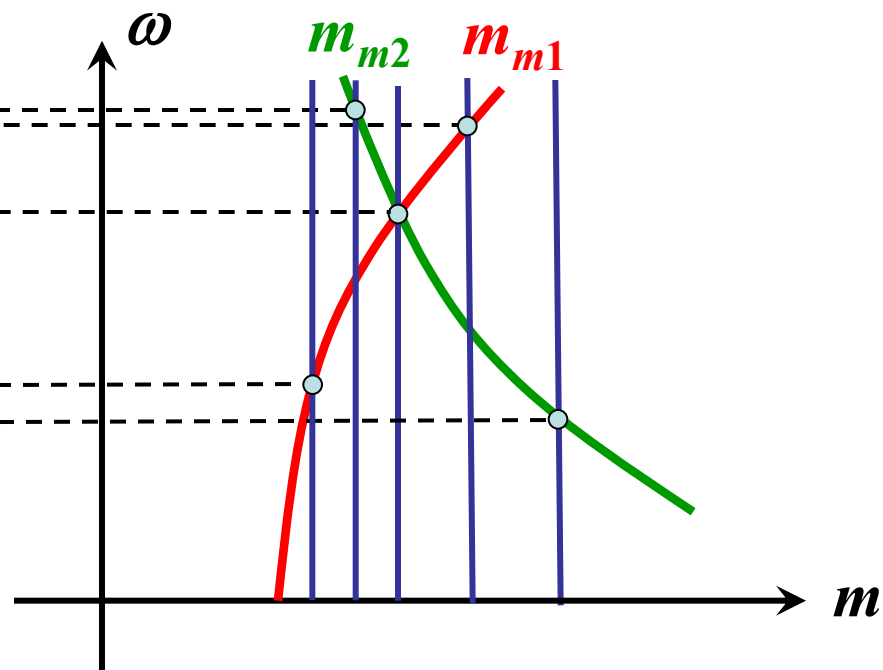
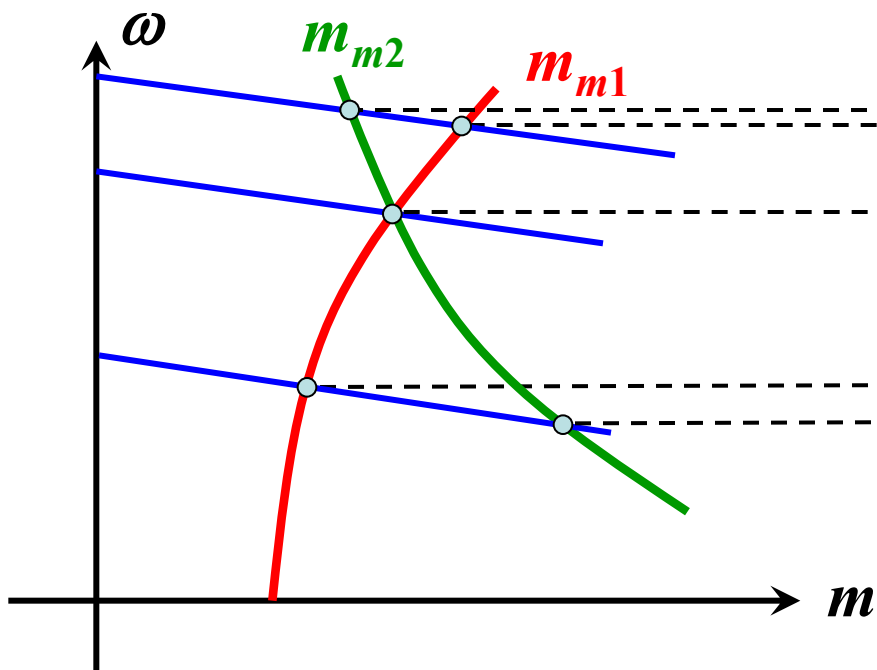
# Strujni izvor



# Poređenje statičkih mehaničkih karakteristika

Naponski izvor  
(naponsko napajanje)

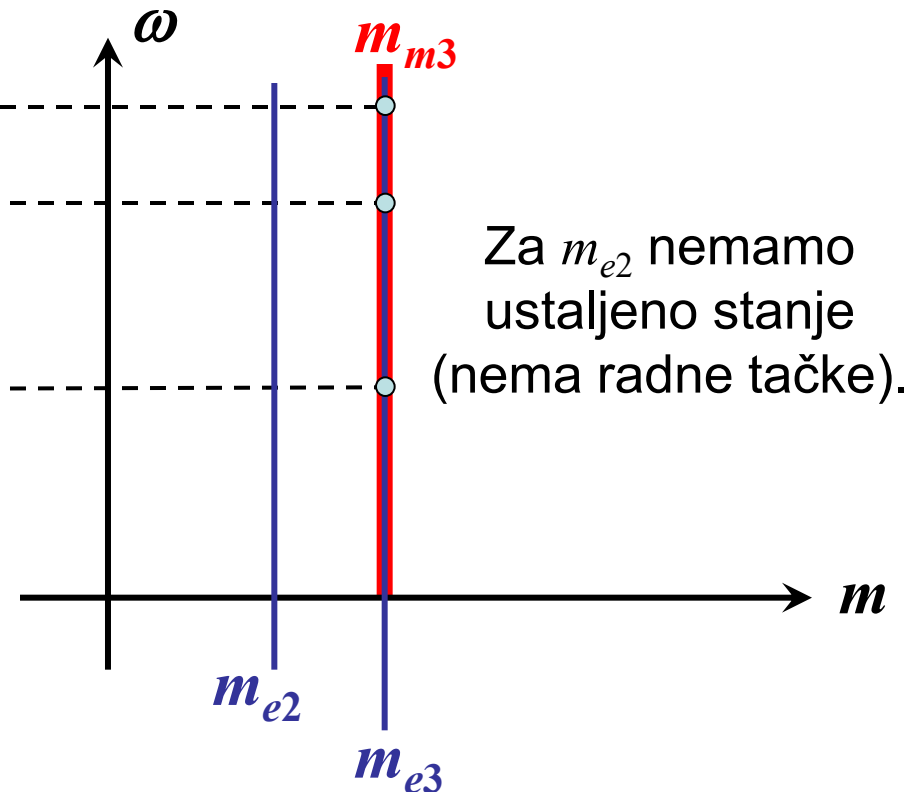
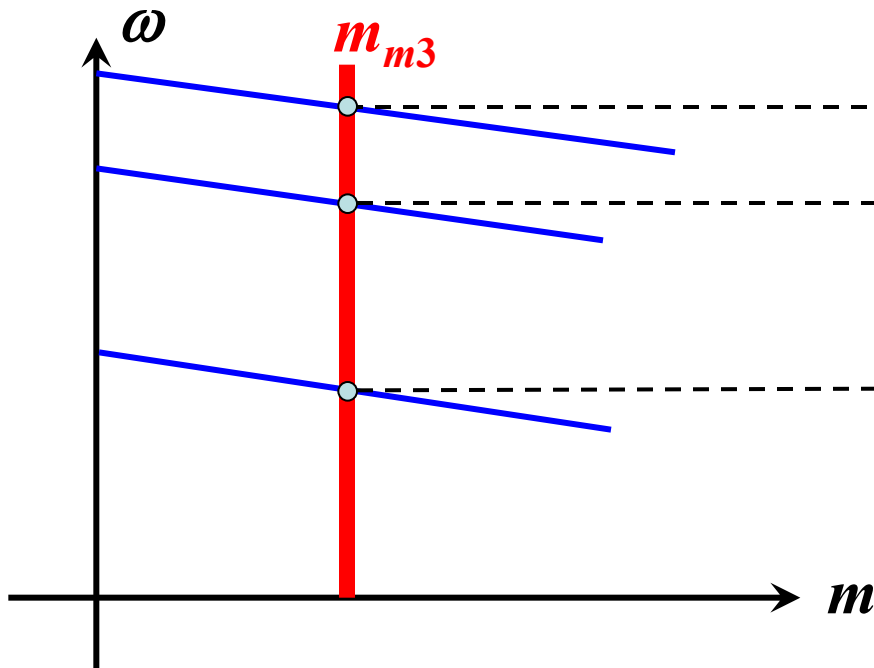
Strujni izvor  
(strujno napajanje)



# Ukoliko je mehanička karakteristika opterećenja nezavisna od brzine

Naponski izvor  
(naponsko napajanje)

Strujni izvor  
(strujno napajanje)



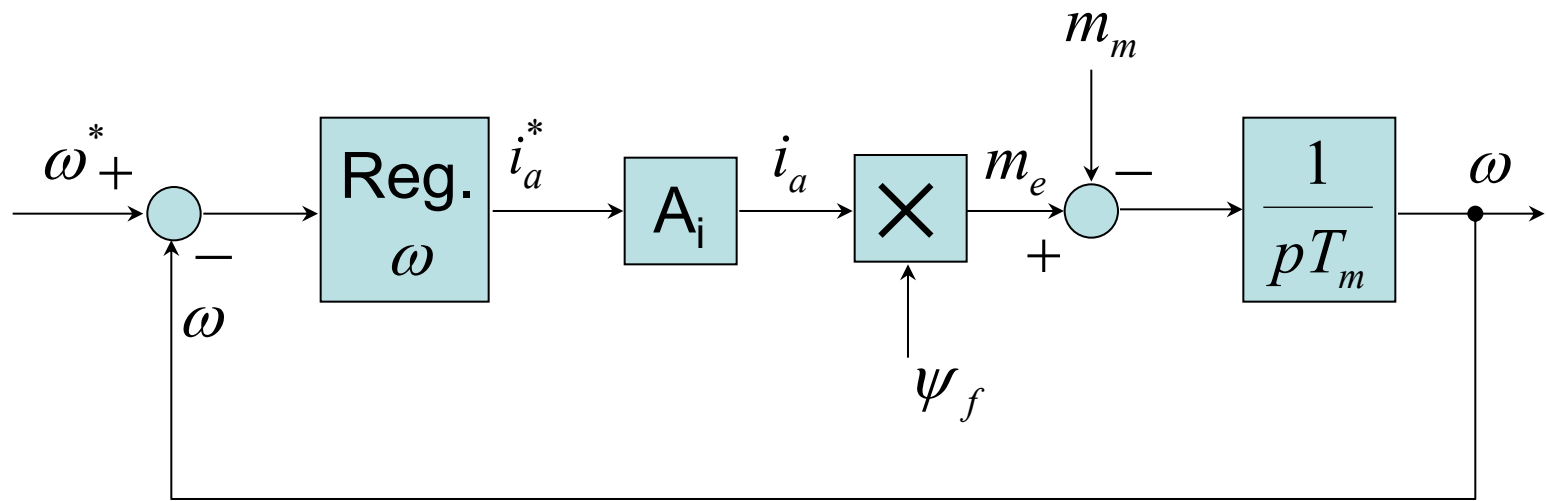
## Naponsko napajanje:

- sporiji odziv
- statička stabilnost radne tačke
- nema kontrole nad strujom (prevazilazi se regulatorom struje)

## Strujno napajanje:

- brži odziv (!)
- statička stabilnost radne tačke - prevazilazi se regulatorom brzine
- neposredna kontrola nad strujom (momentom)

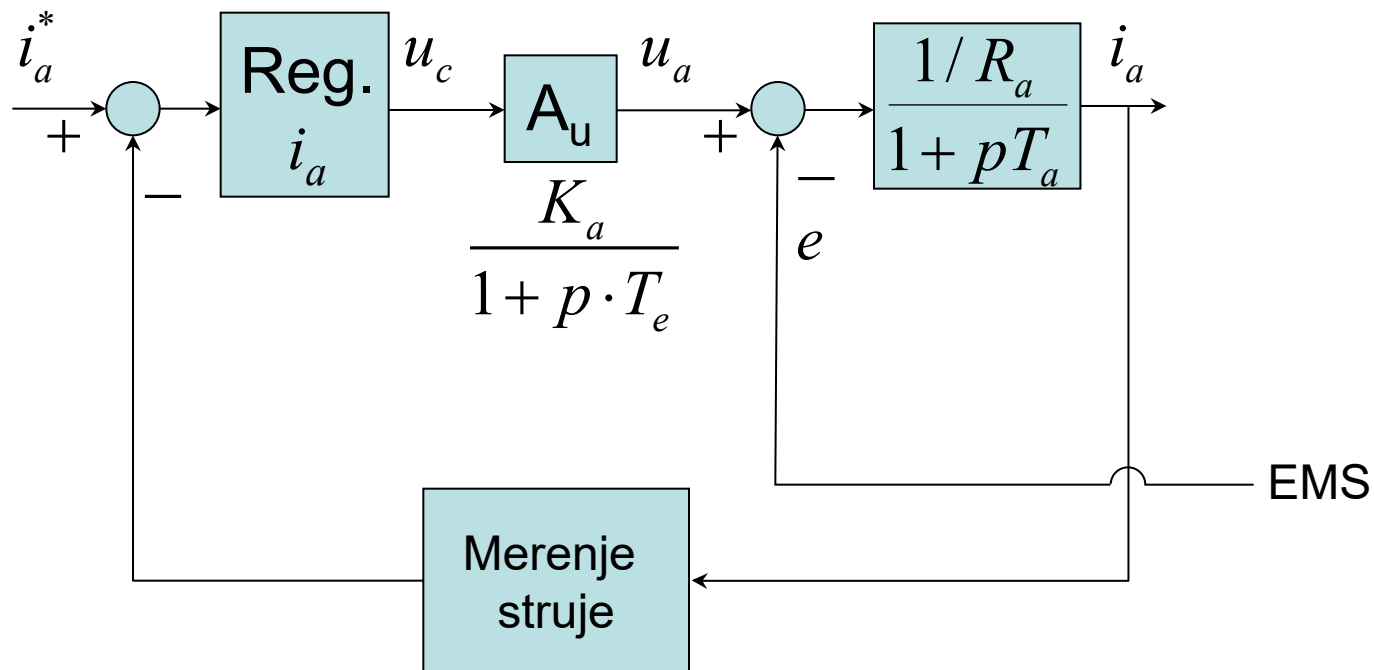
# Regulisani pogon sa regulatorom brzine sa jednosmernim motorom napajanim iz strujnog izvora



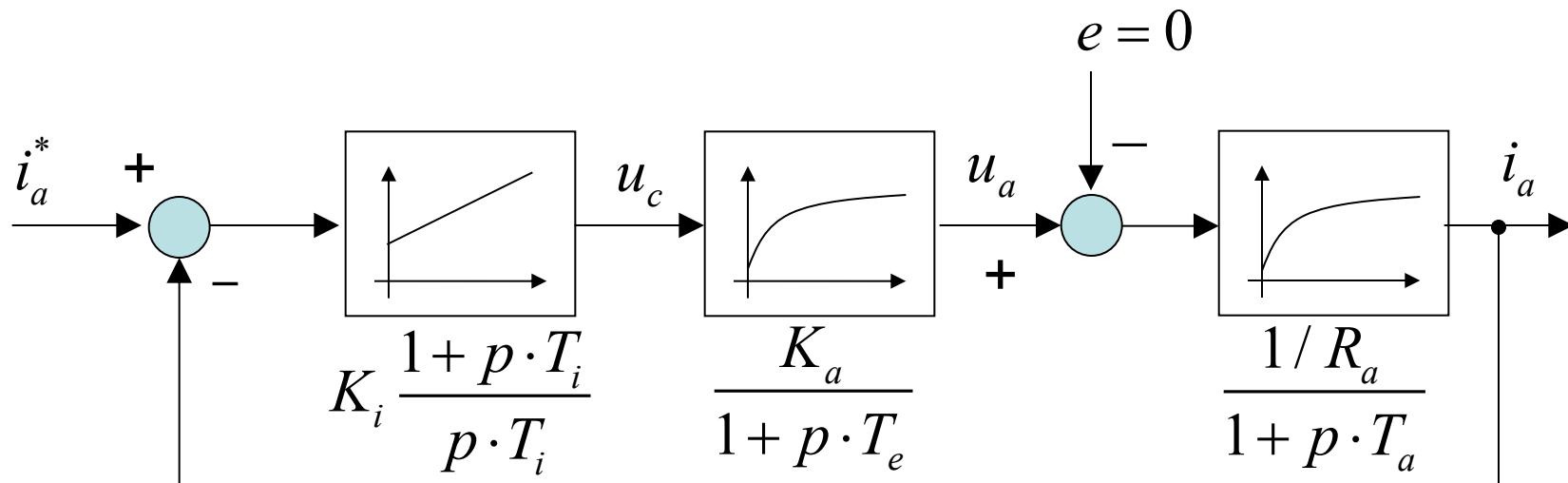


# Poděšavanje parametara regulatora struje

Blok dijagram sistema



# Blok dijagram konture regulacije struje



$$F_{0i}(p) = K_i \cdot \frac{1 + p \cdot T_i}{p \cdot T_i} \cdot \frac{K_a}{1 + p \cdot T_e} \cdot \frac{1 / R_a}{1 + p \cdot T_a} \quad T_a \gg T_e$$

Zanemarili smo blok (senzor) za merenje struje, smatramo da je idealan. Aktuator ima pojačanje i kašnjenje (uprošćeno).

Zanemarili smo uticaj elektromotorne sile, pošto se sporo menja. Smatramo da je to za konturu regulacije struje poremećaj, i u postupku podešavanja parametara vrednost je  $e=0$

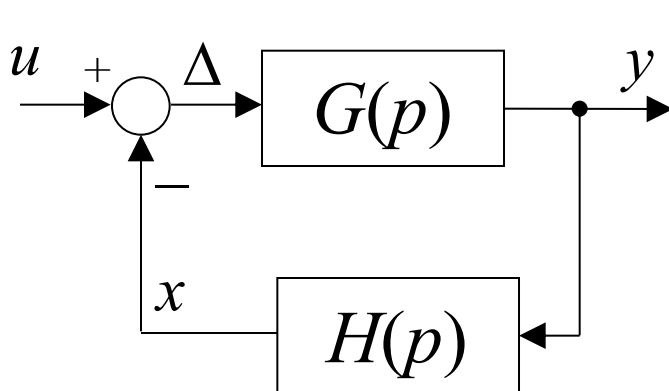
# Funkcija prenosa konture regulacije struje

$$F_{0i}(p) = K_i \cdot \frac{1 + p \cdot T_i}{p \cdot T_i} \cdot \frac{K_a}{1 + p \cdot T_e} \cdot \frac{1/R_a}{1 + p \cdot T_a} \quad T_a \gg T_e$$

Izvršimo kompenzaciju veće vremenske konstante

$$\rightarrow T_i = T_a$$

$$F_{0i}(p) = \frac{K_i \cdot K_a \cdot 1/R_a}{p \cdot T_i \cdot (1 + p \cdot T_e)}$$



$$\frac{y}{u}(p) = \frac{G(p)}{1 + G(p) \cdot H(p)} \quad H(p) = 1$$

$$F_{wi}(p) = \frac{F_{0i}(p)}{1 + F_{0i}(p)}$$

# Izbor parametara regulatora

$$F_{wi}(p) = \frac{K_i \cdot K_a \cdot (1/R_a)}{K_i \cdot K_a \cdot (1/R_a) + p \cdot T_i + p^2 \cdot T_i \cdot T_e}$$

$$a_0 = K_i \cdot K_a \cdot (1/R_a); \quad a_1 = T_i; \quad a_2 = T_i \cdot T_e$$

Primenjujemo definisan kriterijum  
optimizacije modula funkcije prenosa

$$a_1^2 = 2 \cdot a_0 \cdot a_2$$

$$K_i \cdot K_a \cdot 1/R_a = \frac{T_i}{2 \cdot T_e} \longrightarrow$$

$$K_i = \frac{T_i}{2 \cdot K_a \cdot (1/R_a) \cdot T_e}$$

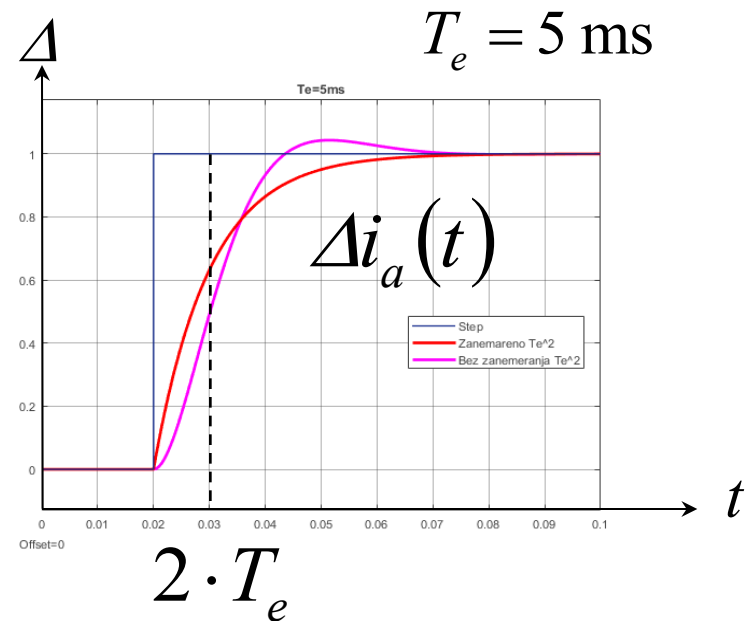
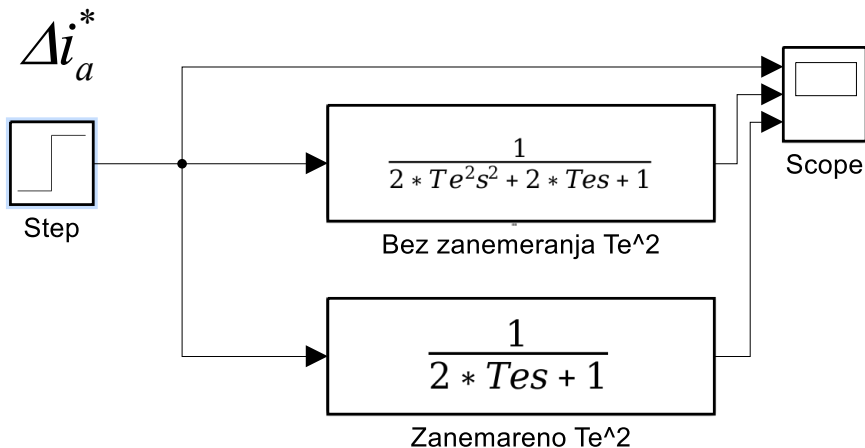
$$F_{wi}(p)_{opt.} = \frac{i_a(p)}{i_a^*(p)} = \frac{1}{1 + p \cdot 2 \cdot T_e + p^2 \cdot 2 \cdot T_e^2}$$

Brzina promene brzine je značajno manja od brzine promene struje indukta  $i_a$ .

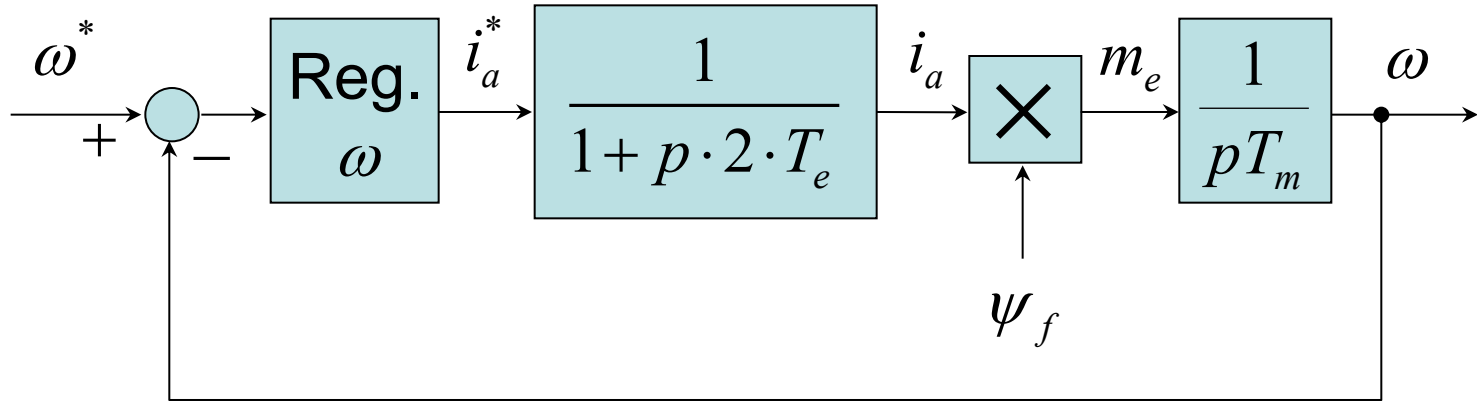
Pri promeni  $\Delta i_a^* \sim \Delta i_a$  važi  $\Delta \omega \approx 0$  i  $\Delta e \approx 0$

Ukoliko vremenska konstanta  $T_e$  ima malu vrednost, možemo zanemariti kvadratni član.

$$\frac{1}{1 + p \cdot 2 \cdot T_e + \underbrace{p^2 \cdot 2 \cdot T_e^2}_{\approx 0}} \approx \frac{1}{1 + p \cdot 2 \cdot T_e}$$



## Regulator brzine:



$$F_{\omega}(p) = K_{\omega} \cdot \frac{1 + p \cdot T_{\omega}}{p \cdot T_{\omega}}$$

$$F_{0\omega}(p) = \frac{K_{\omega} \cdot (1 + p \cdot T_{\omega}) \cdot \psi_f}{p^2 \cdot T_{\omega} \cdot T_m \cdot (1 + p \cdot 2 \cdot T_e)} = \frac{K'_{\omega} \cdot (1 + p \cdot T_{\omega})}{p^2 \cdot T_{\omega} \cdot T_m \cdot (1 + p \cdot 2 \cdot T_e)}$$

$$K'_{\omega} = K_{\omega} \cdot \psi_f$$

$$F_{w\omega}(p) = \frac{F_{0\omega}(p)}{1 + F_{0\omega}(p)}$$

# Funkcija spregnutog prenosa brzinske petlje

$$F_{w\omega}(p) = \frac{K'_\omega \cdot (1 + p \cdot T_\omega)}{p^2 \cdot T_\omega \cdot T_m \cdot (1 + p \cdot 2 \cdot T_e) + K'_\omega \cdot (1 + p \cdot T_\omega)}$$

$$F_{w\omega}(p) = \frac{K'_\omega \cdot (1 + p \cdot T_\omega)}{p^3 \cdot \underbrace{T_\omega \cdot T_m \cdot 2 \cdot T_e}_{a_3} + p^2 \cdot \underbrace{T_\omega \cdot T_m}_{a_2} + p \cdot \underbrace{T_\omega \cdot K'_\omega}_{a_1} + \underbrace{K'_\omega}_{a_0}}$$

Primenom optimizacije:  $a_1^2 = (a) \cdot a_0 \cdot a_2$      $a_2^2 = (a) \cdot a_1 \cdot a_3$

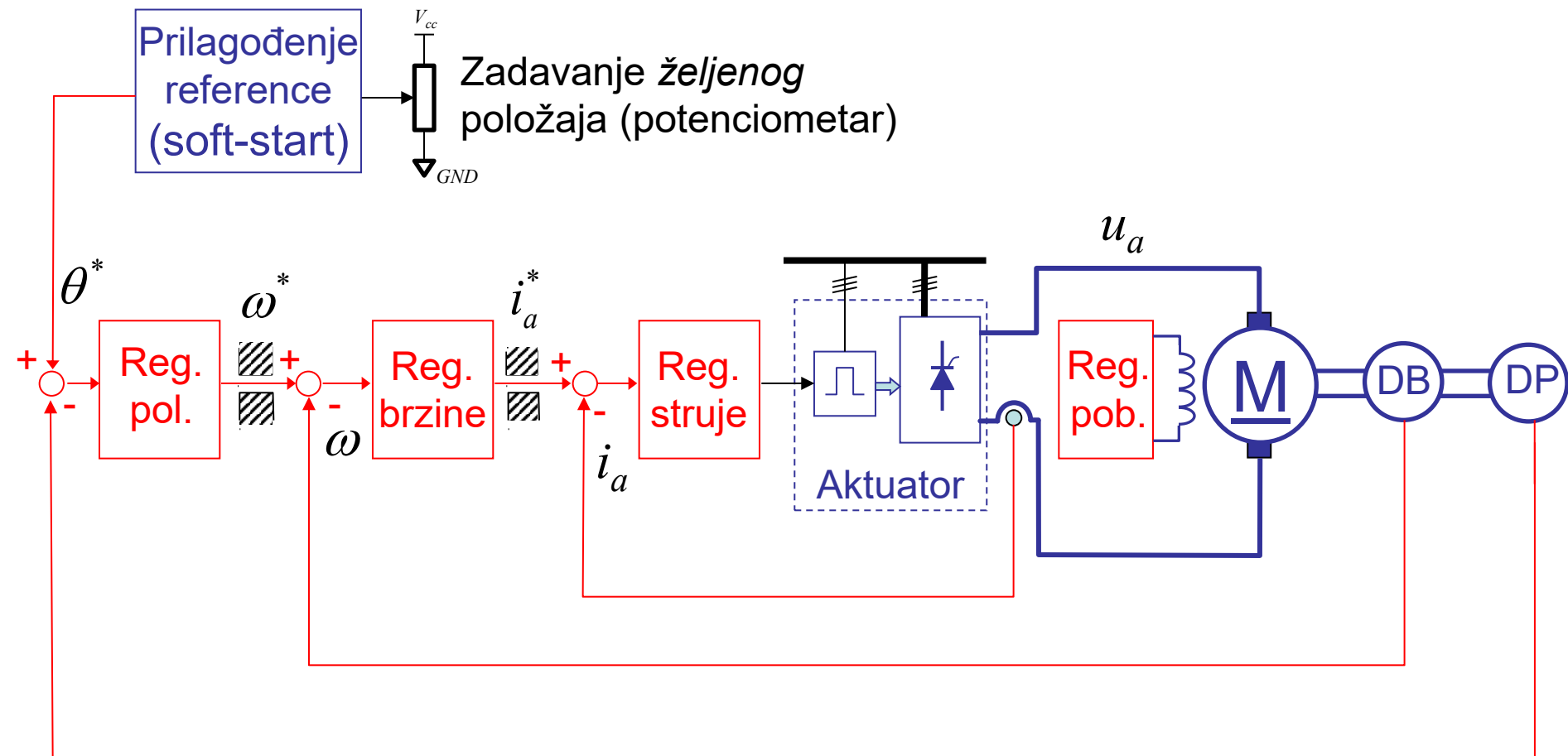
$$T_\omega = a^2 \cdot 2 \cdot T_e; \quad K'_\omega = \frac{1}{a} \cdot \frac{T_m}{2 \cdot T_e}$$

gde je  $a = 2\zeta + 1$

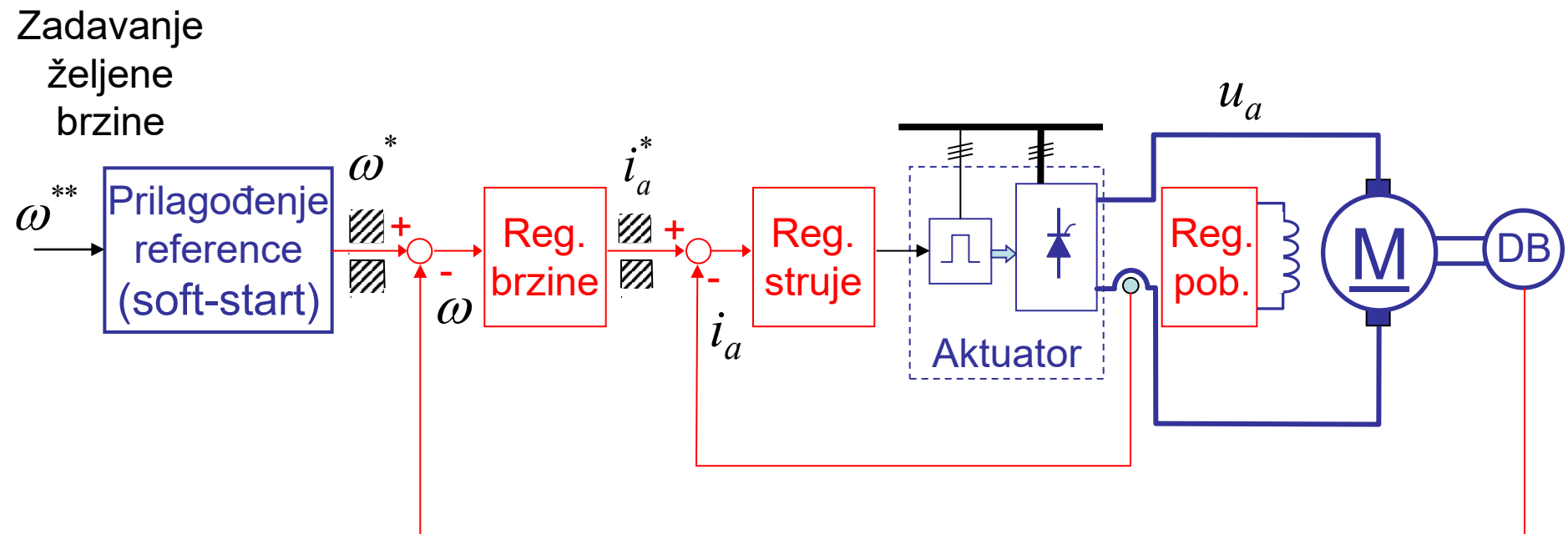
$\zeta$  - željeni relativni faktor prigušenja zatvorene brzinske petlje.

Sledi da je: 
$$K_\omega = \frac{1}{\psi_f} \cdot \frac{T_m}{a \cdot 2 \cdot T_e}$$

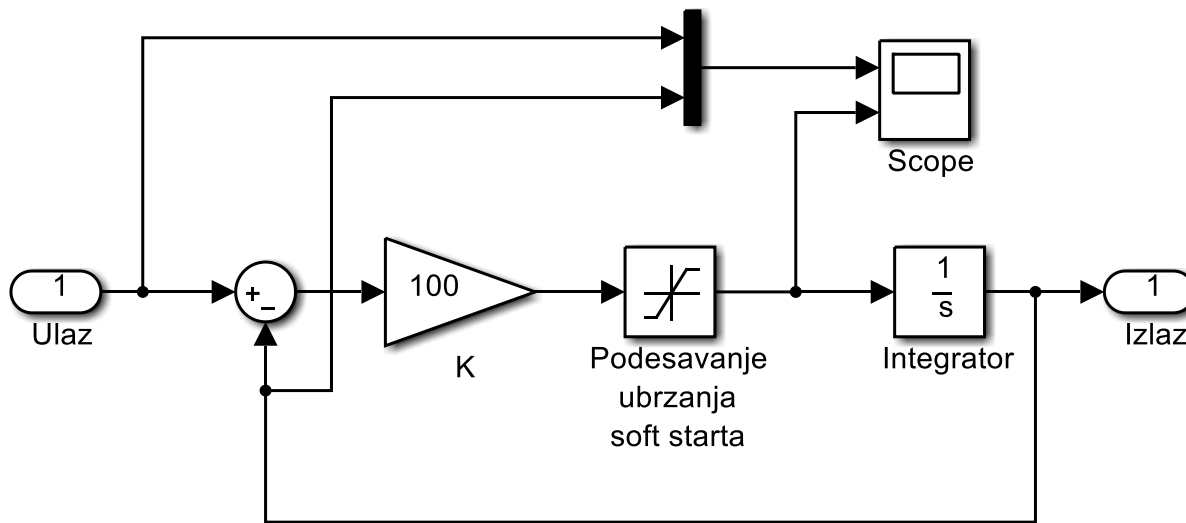
# Regulisani elektromotorni pogon sa motorom jednosmerne struje - osnovna struktura



# Regulisani elektromotorni pogon sa motorom jednosmerne struje bez regulacije položaja

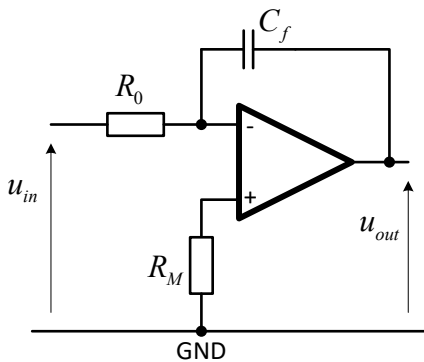


# Realizacija bloka za prilagođenje reference

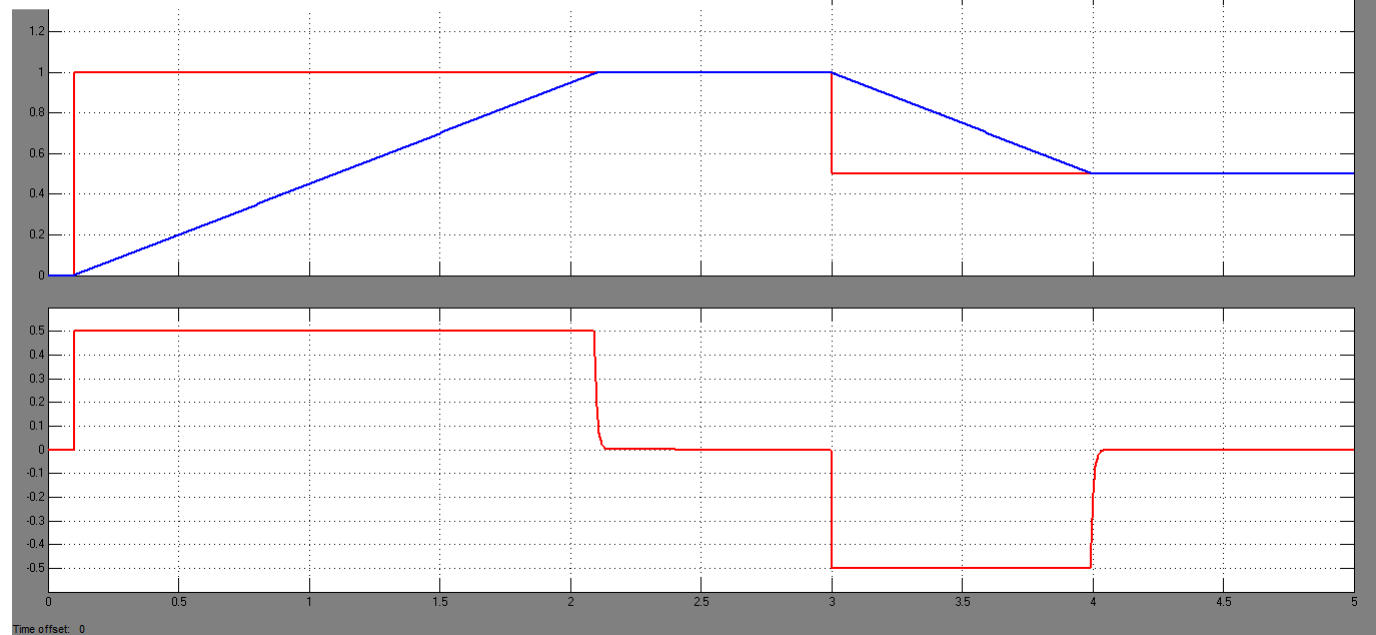


Integrator u kontinualnom vremenskom domenu

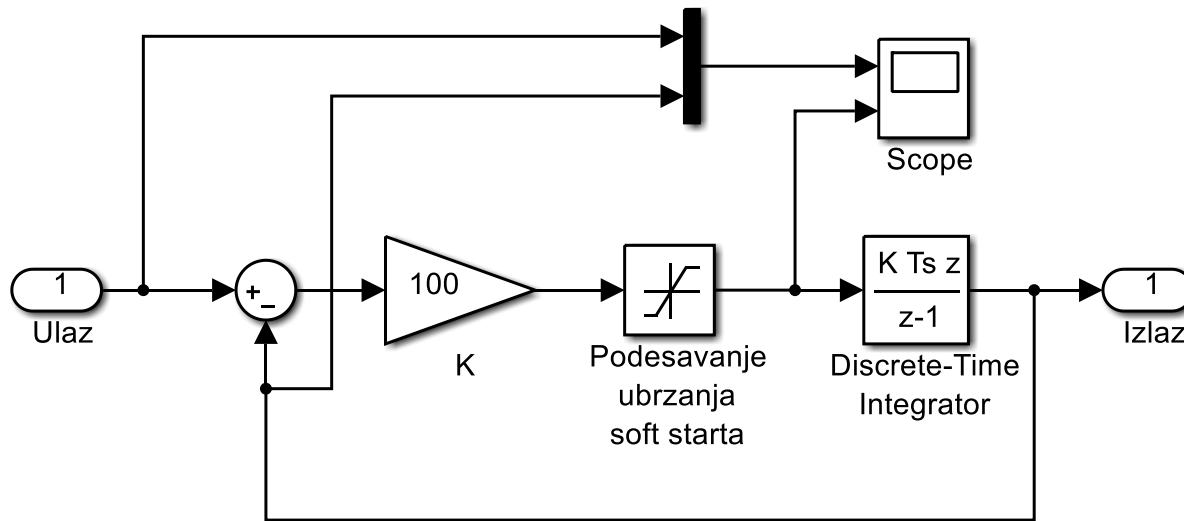
Limit =  $\pm 0,5$



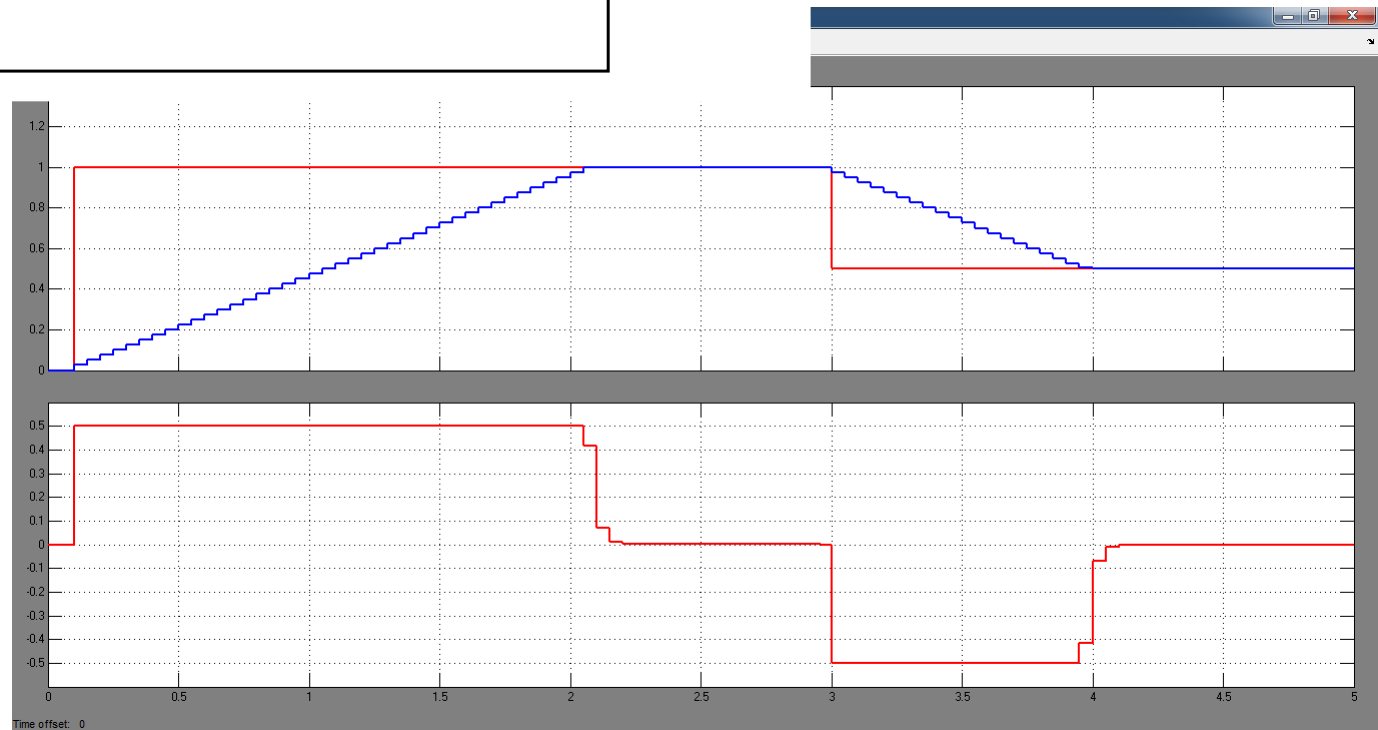
Invertuje signal



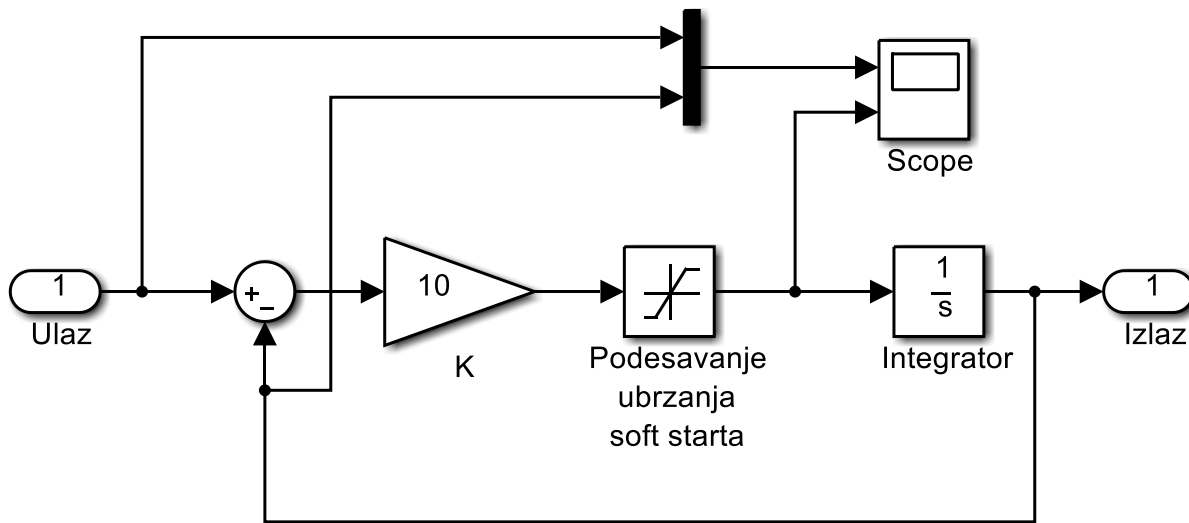
# Realizacija bloka za prilagođenje reference



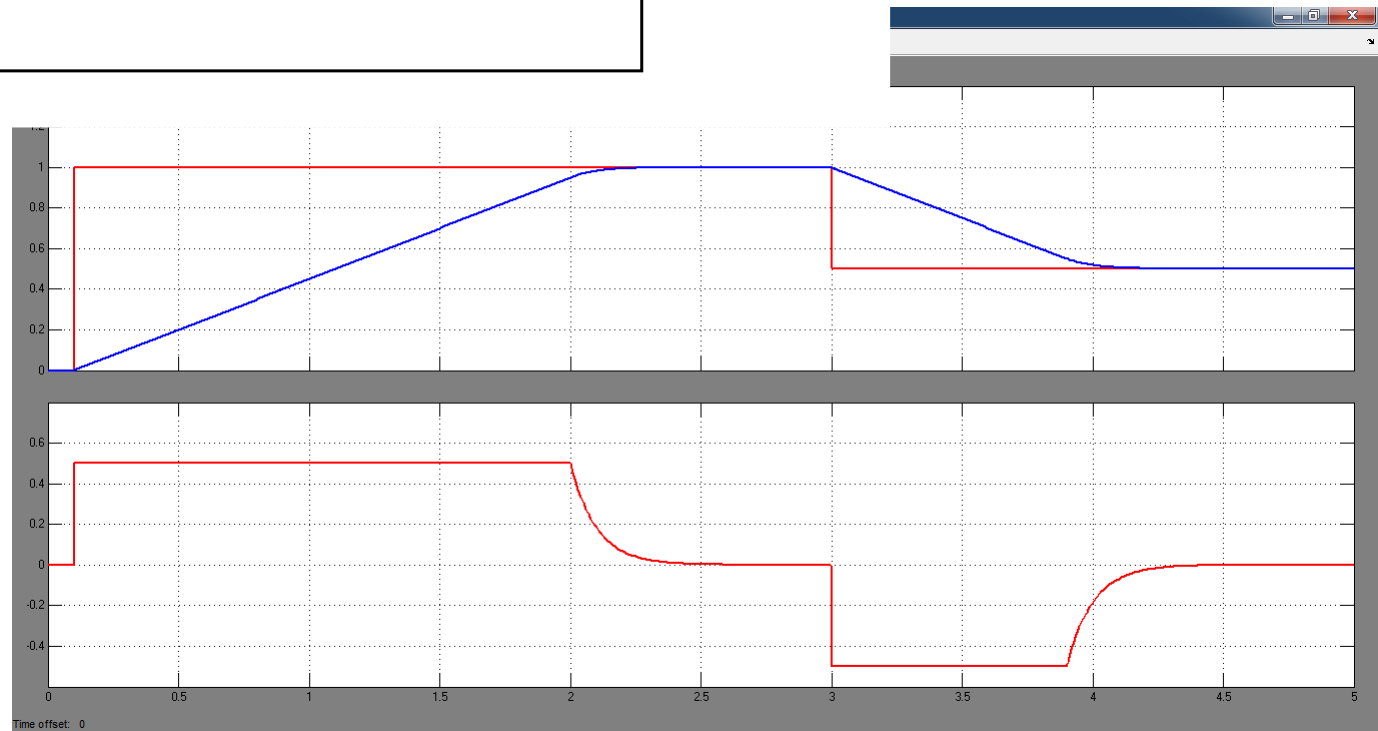
Integrator u diskretnom vremenskom domenu



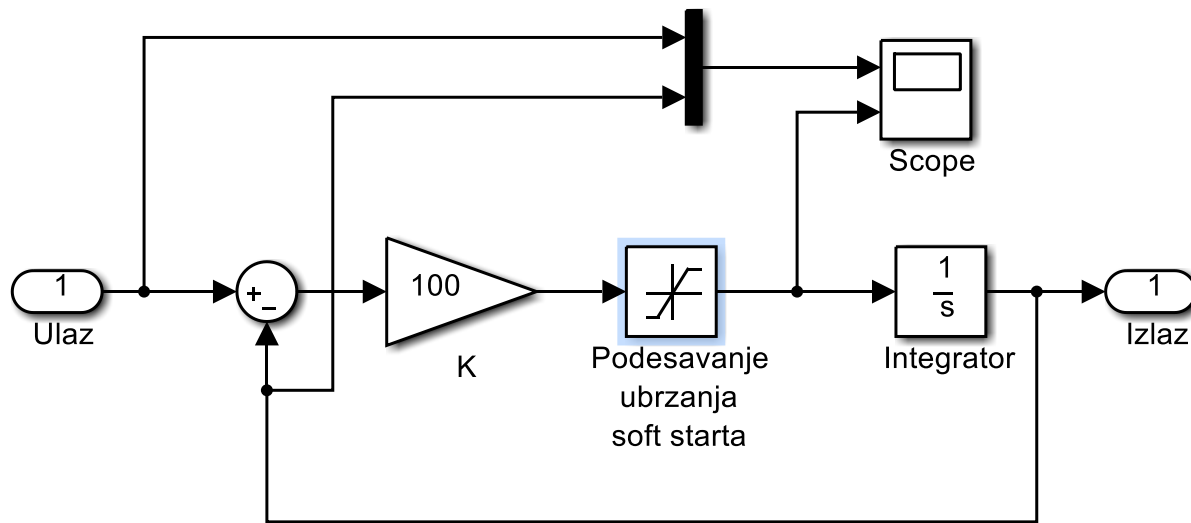
# Realizacija bloka za prilagođenje reference



Uticaj  
pojačanja

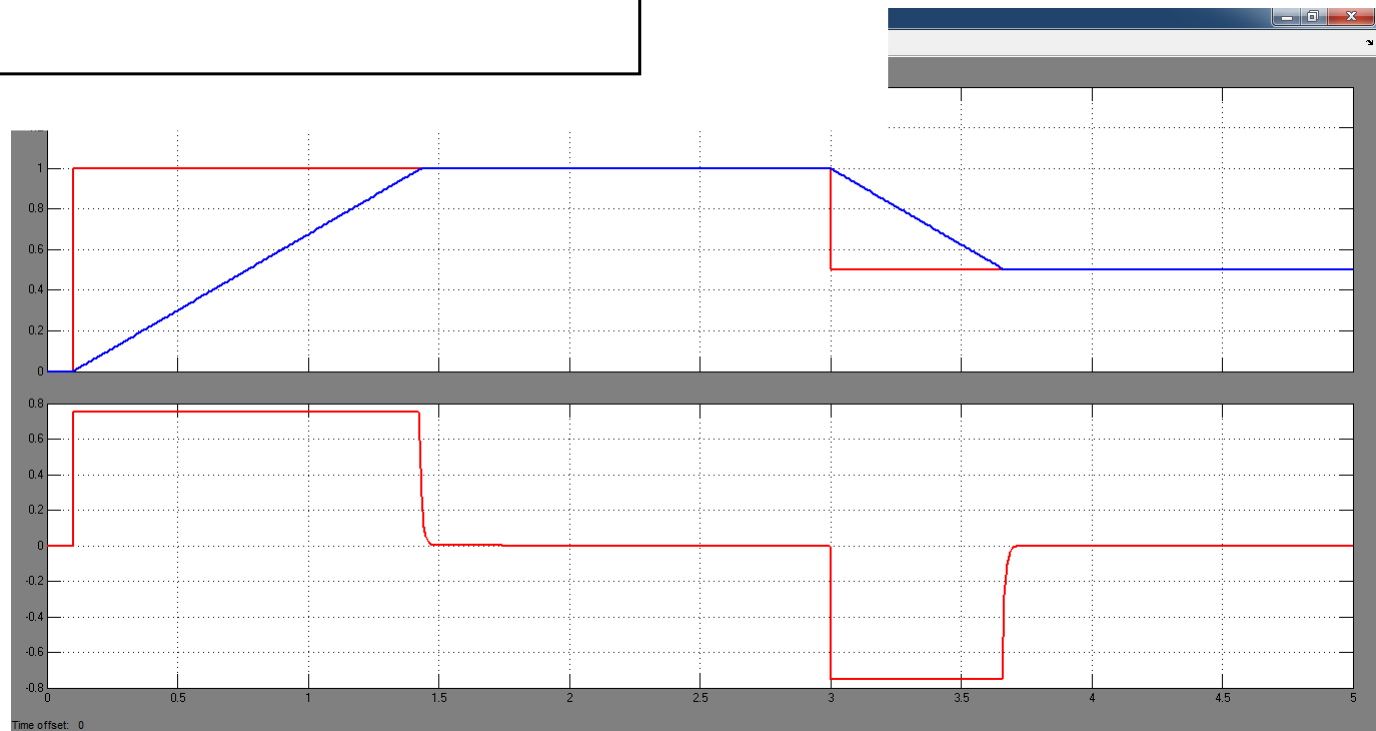


# Realizacija bloka za prilagođenje reference

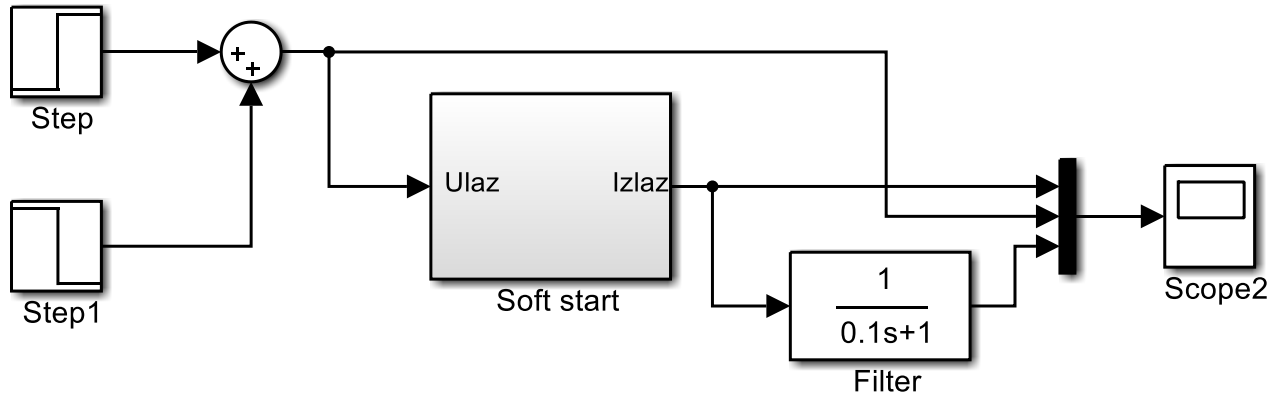


Uticaj  
promene limita  
na ubrzanje

Limit =  $\pm 0,75$



# Realizacija bloka za prilagođenje reference

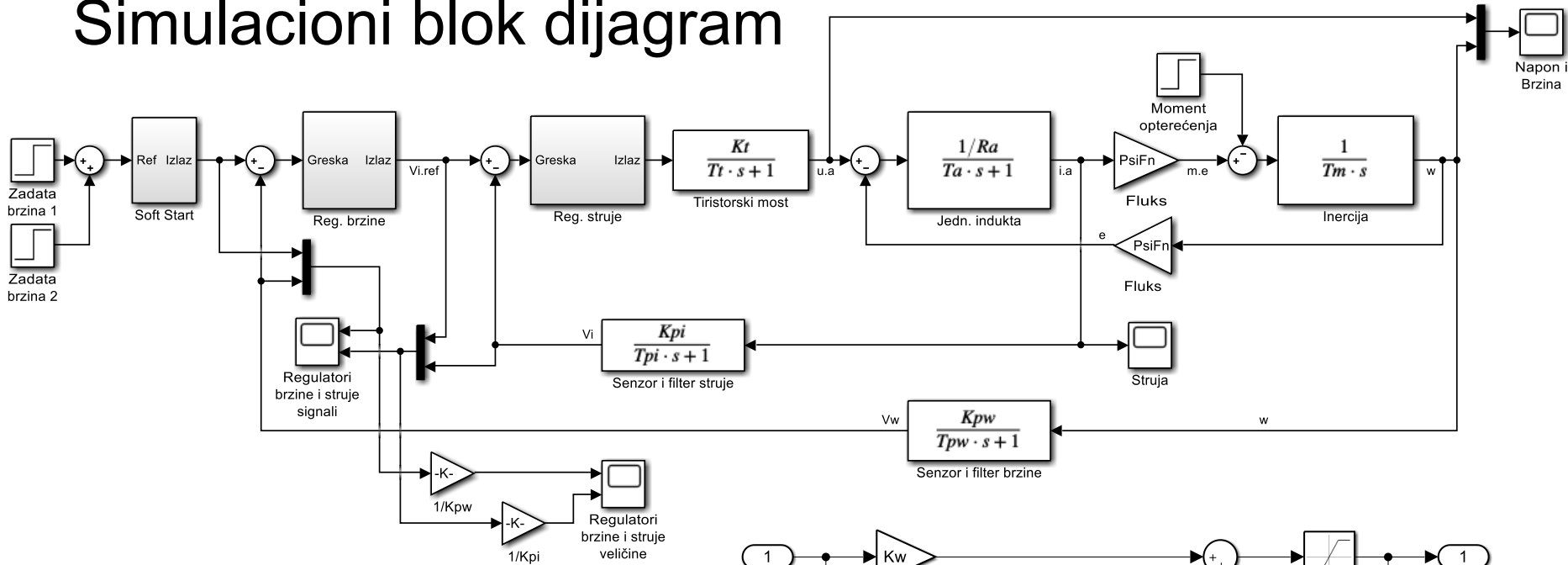


Soft-start  
+  
filter

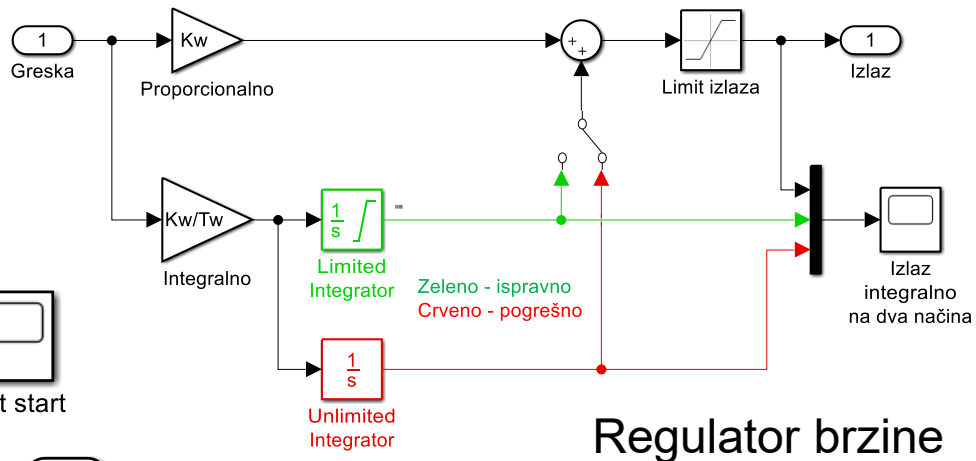
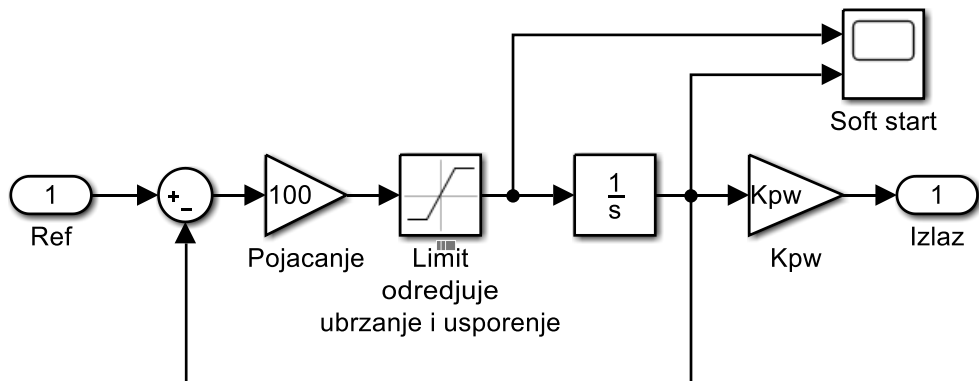
Limit =  $\pm 1,5$



# Simulacioni blok dijagram



## Soft start



Regulator struje ima isti blok dijagram, ali druge parametre: pojačanje ( $K_i$ ), vremensku konstantu integralnog dejstva ( $T_i$ ) i limite integralnog dejstva i izlaza (LIM\_UC)

# Parametri

```
Ra = 0.075;
% u relativnim jedinicama
PsiFn = 1-Ra;
Ta = 30e-3;
Tm = 1.92;
Mmn = PsiFn;
mm = Mmn/2;

ktg = 0.05;
Kpw = ktg;
Tpw = 52.8e-3;
Kpi = 0.025;
Tpi = 2.6e-3;
Tt = 1.66e-3;
Kt = 30;

Te = Tt+Tpi;
Te2 = 2*Te+Tpw;

% reg. struje
Ti = Ta;
Ki = Ta/(2*Kt*Kpi*(1/Ra)*Te);
% reg. brzine
Tw = 4*Te2;
Kw = (Tm*Kpi)/(2*Te2*Kpw*PsiFn);

Vwref1 = 0.5; % * Kpw;
Vwref2 = 0.25; % * Kpw;
LIM_UC = 1;
LIM_IA = 2 * Kpi;
LIM_SS = 0.5;
```

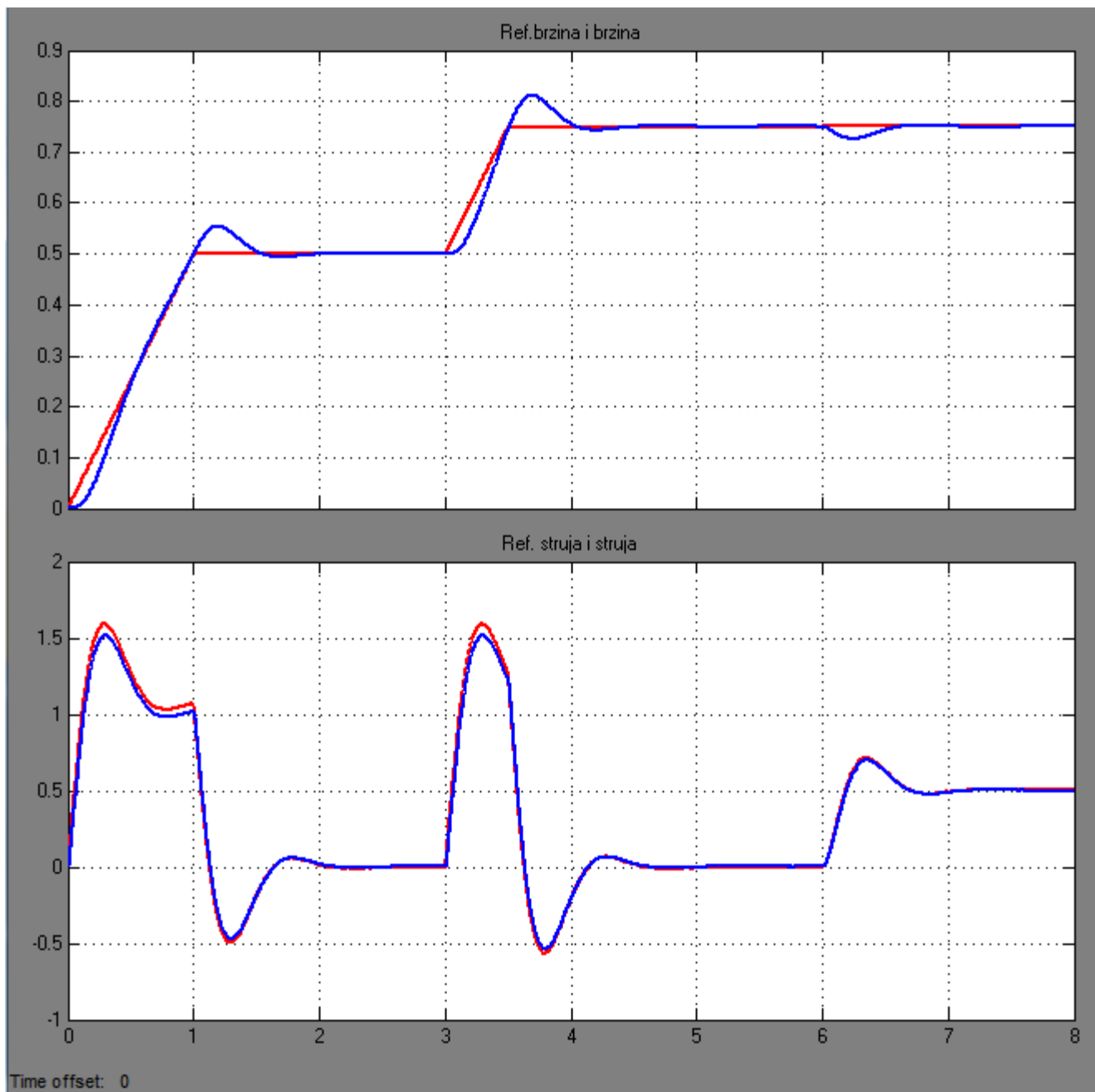
Početa  
zadata brzina  
je

$$0,5 \omega_{nom}$$

U trenutku  
 $t=3s$  zadaje se  
brzina

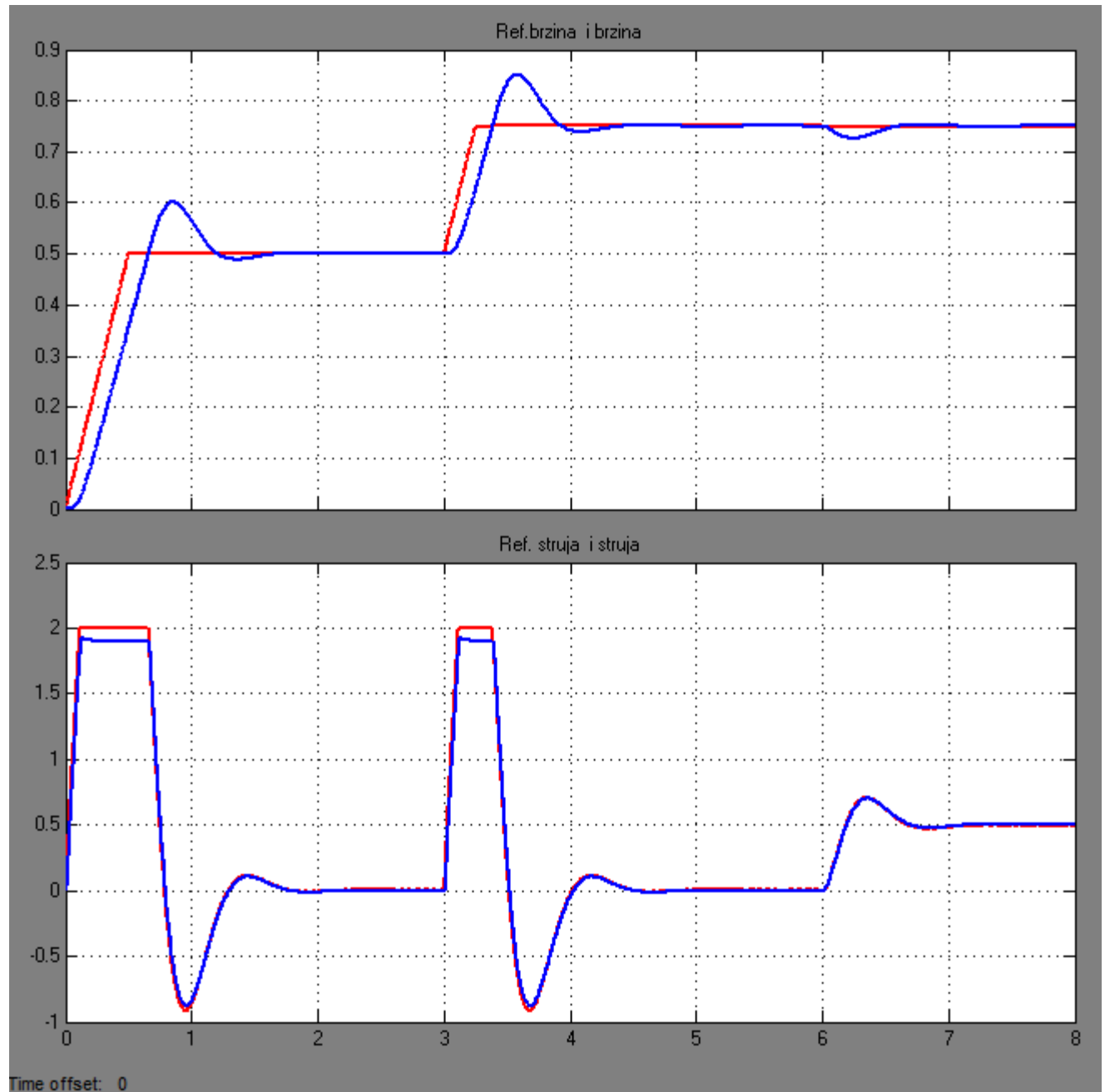
$$0,75 \omega_{nom}$$

Opterećenje  
pogona  
polovinom  
nominalnog  
momenta je u  
 $t = 6s$

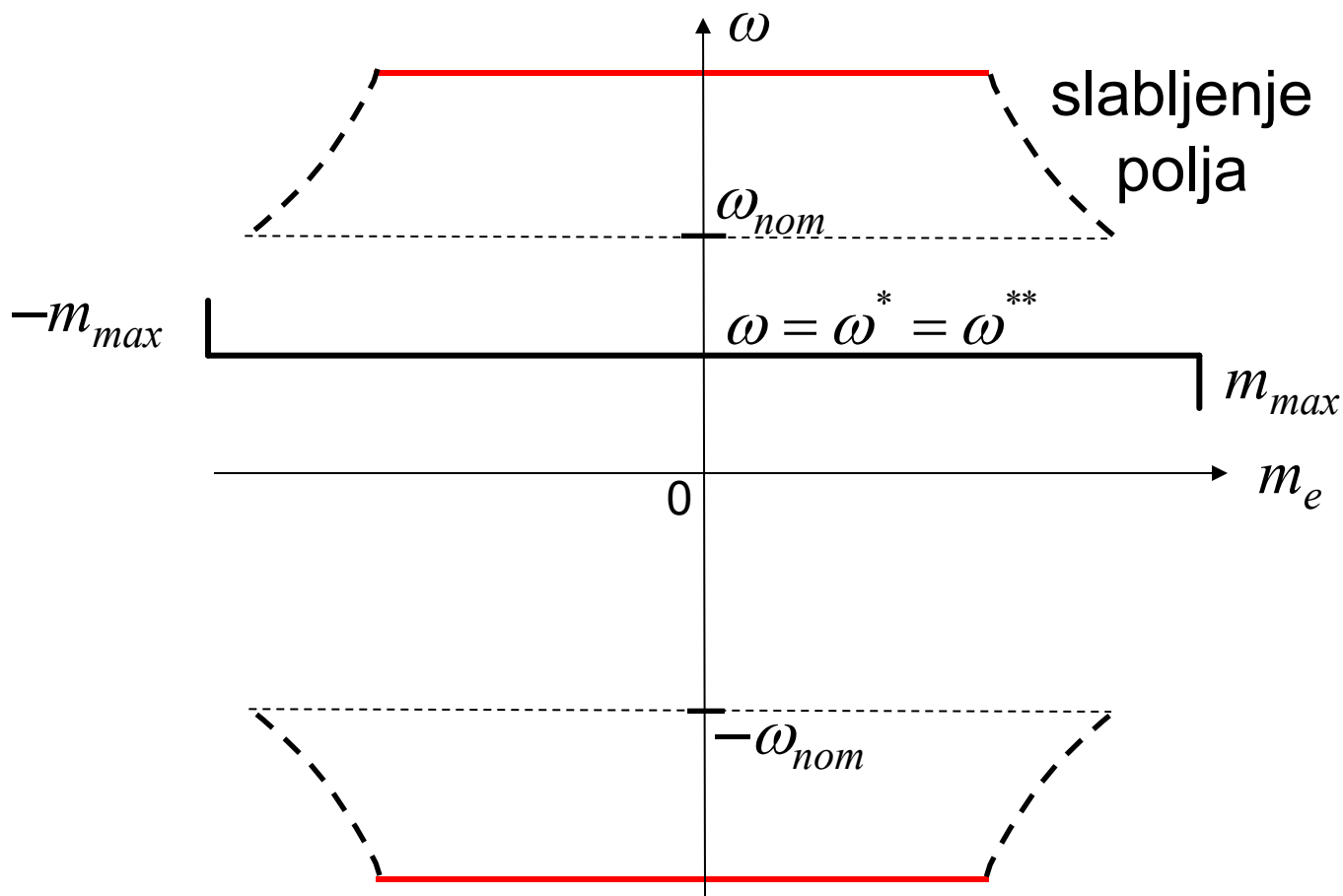


# Uticaj limita momenta na odziv regulatora brzine

Povećano je željeno ubrzanje u bloku soft starta. Zbog ograničenja struje, ne dostiže se zadata brzina u toku soft-starta.

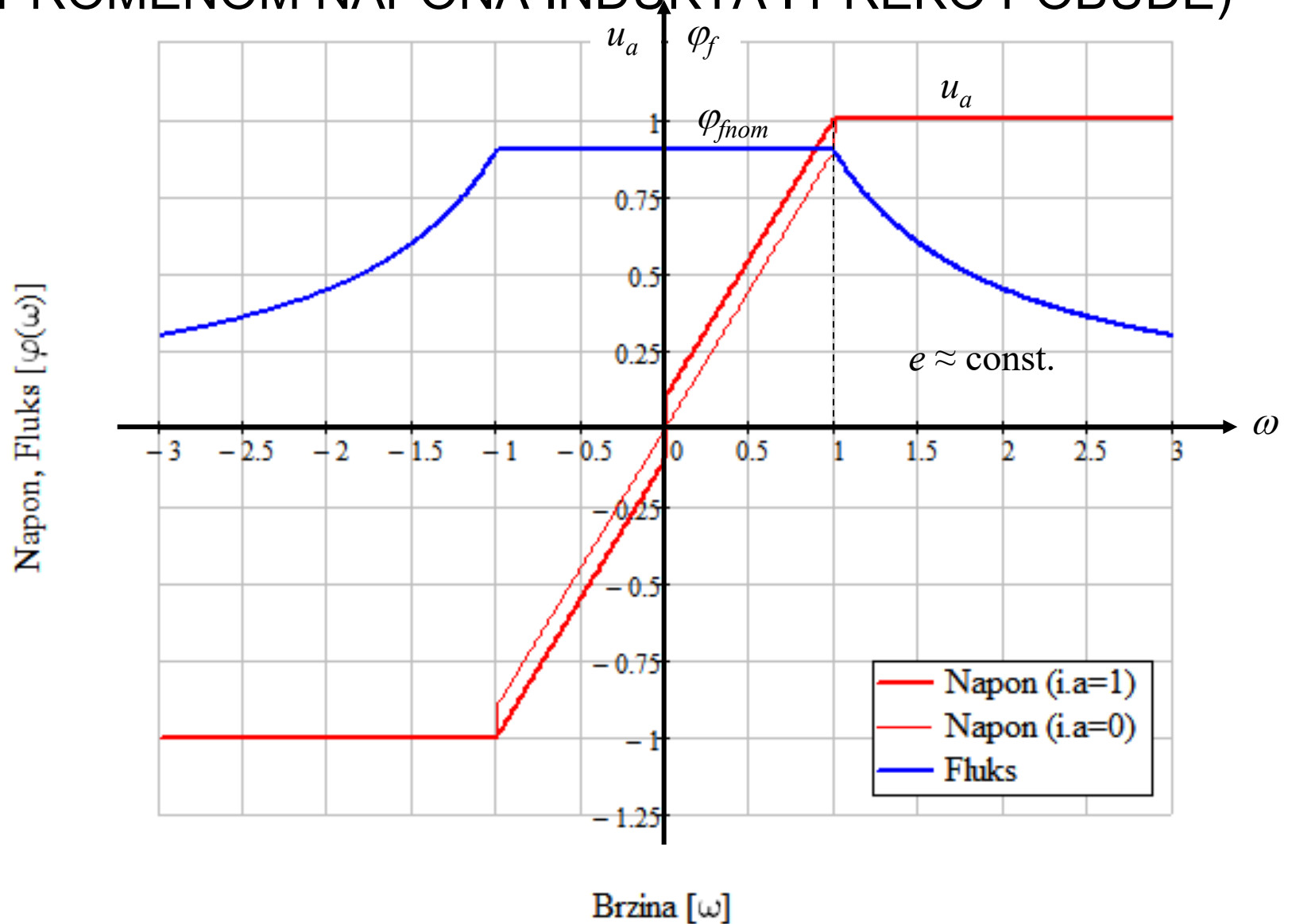


# Statička karakteristika regulisanog pogona



# KOMBINOVANO UPRAVLJANJE (PROMENOM NAPONA INDUKTA I PREKO POBUDE)

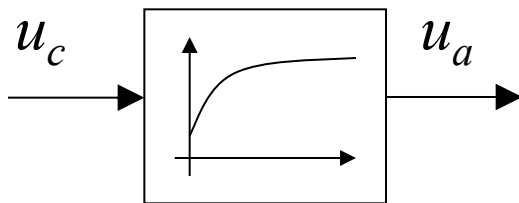
N



# Aktuatori

- ❑ Tiristorski ispravljači  
(mosne sprege, mrežna komutacija)
- ❑ Više-kvadrantni rad
- ❑ Generator jednosmerne struje (Vard Leonard)
- ❑ Čoperi

Uprošćeni blok dijagram  
aktuatora



Uprošćena prenosna funkcija  
aktuatora

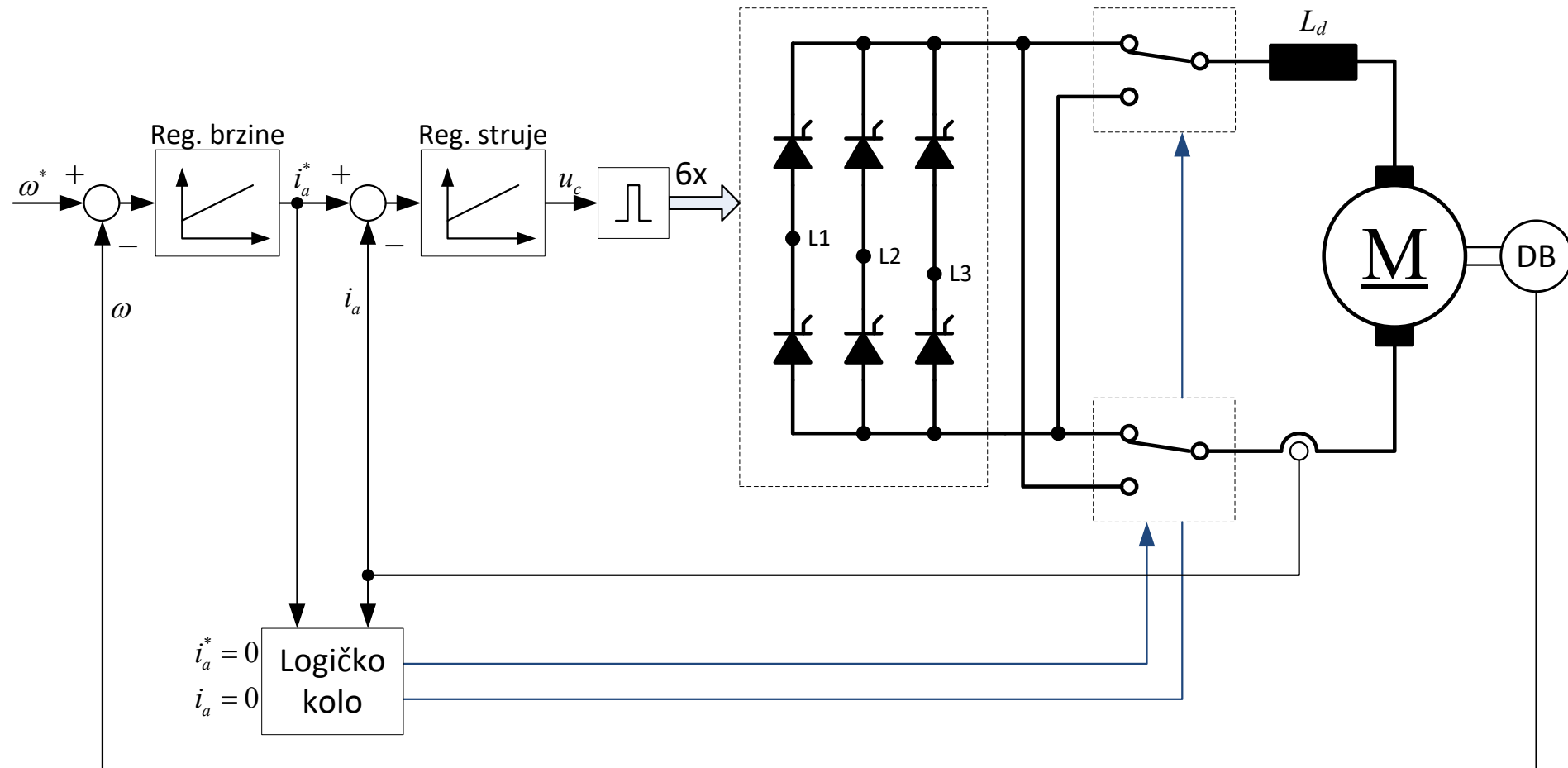
$$\frac{U_a}{U_c}(p) = \frac{K_a}{1 + p \cdot T_{ak}}$$

$T_{ak} = ?$  zavisi od vrste aktuatora

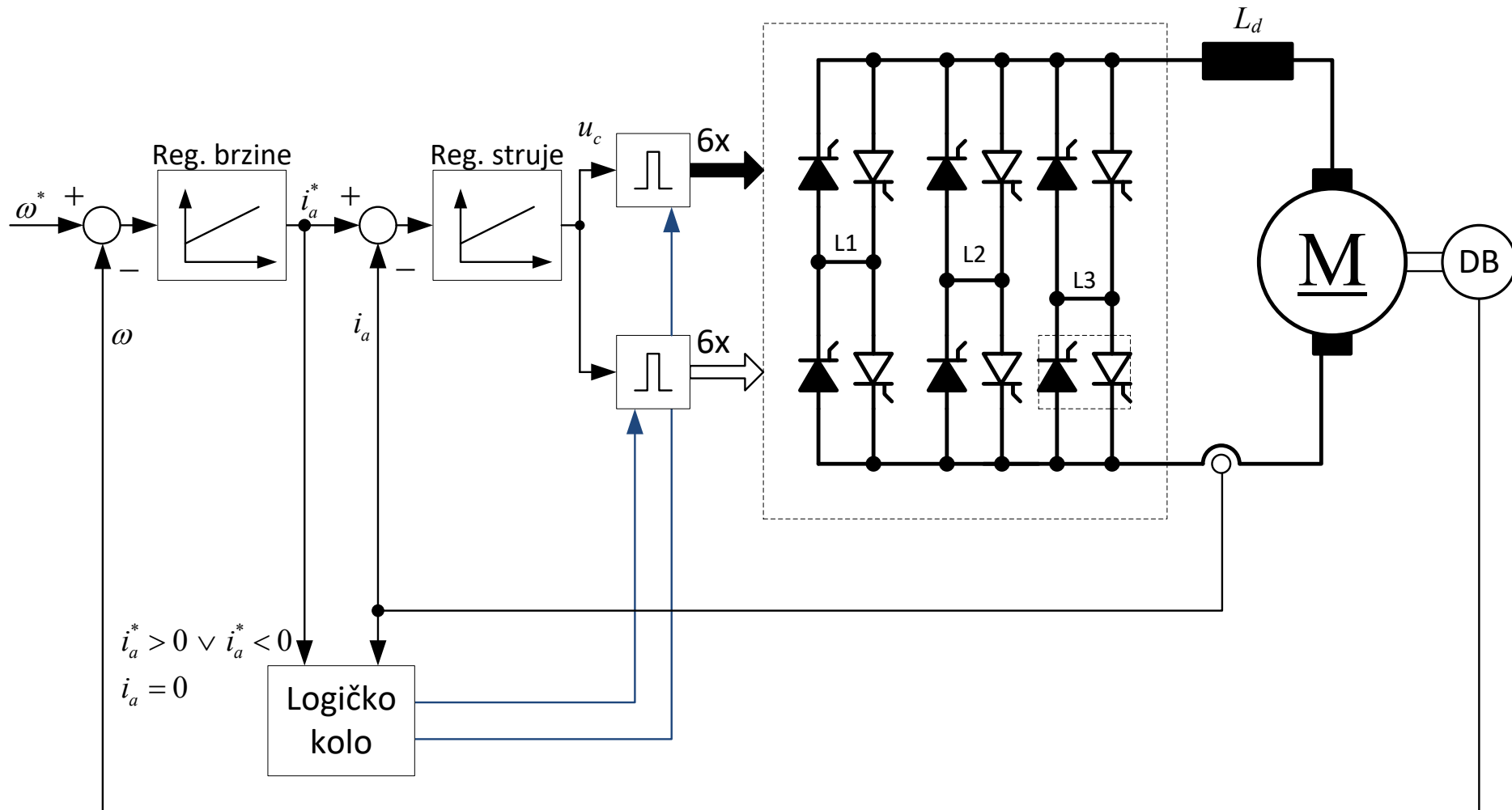
# Četvoro- kvadratni rad sa preklopnikom

Regulacija brzine za male brzine reversa!

Logičko kolo: - promena stanja prekidača samo kada je  $i_a = 0$   
- položaj prekidača u funkciji od znaka  $i_a^*$

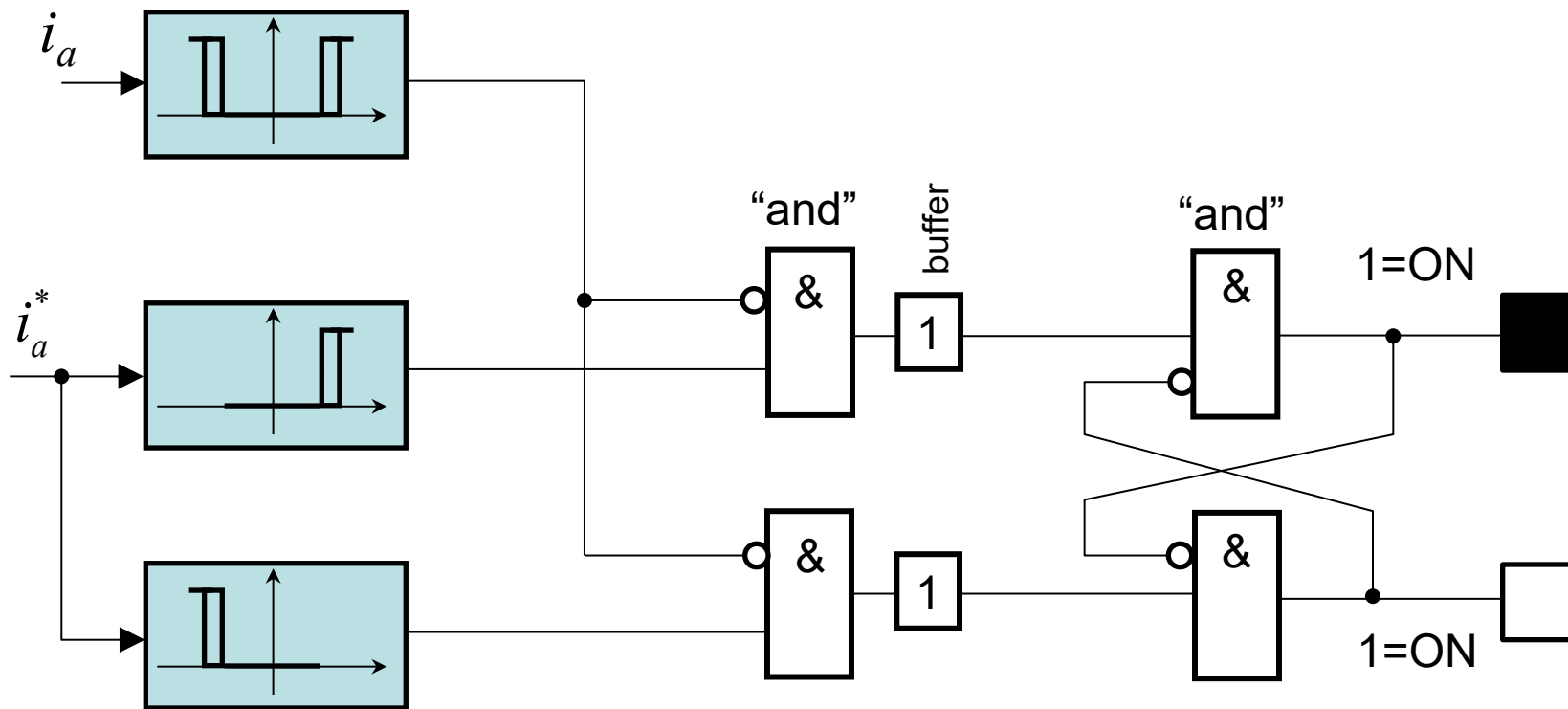


# Četvoro-kvadratni rad sa dva anti-paralelna mosta (razdeljeno upravljanje)



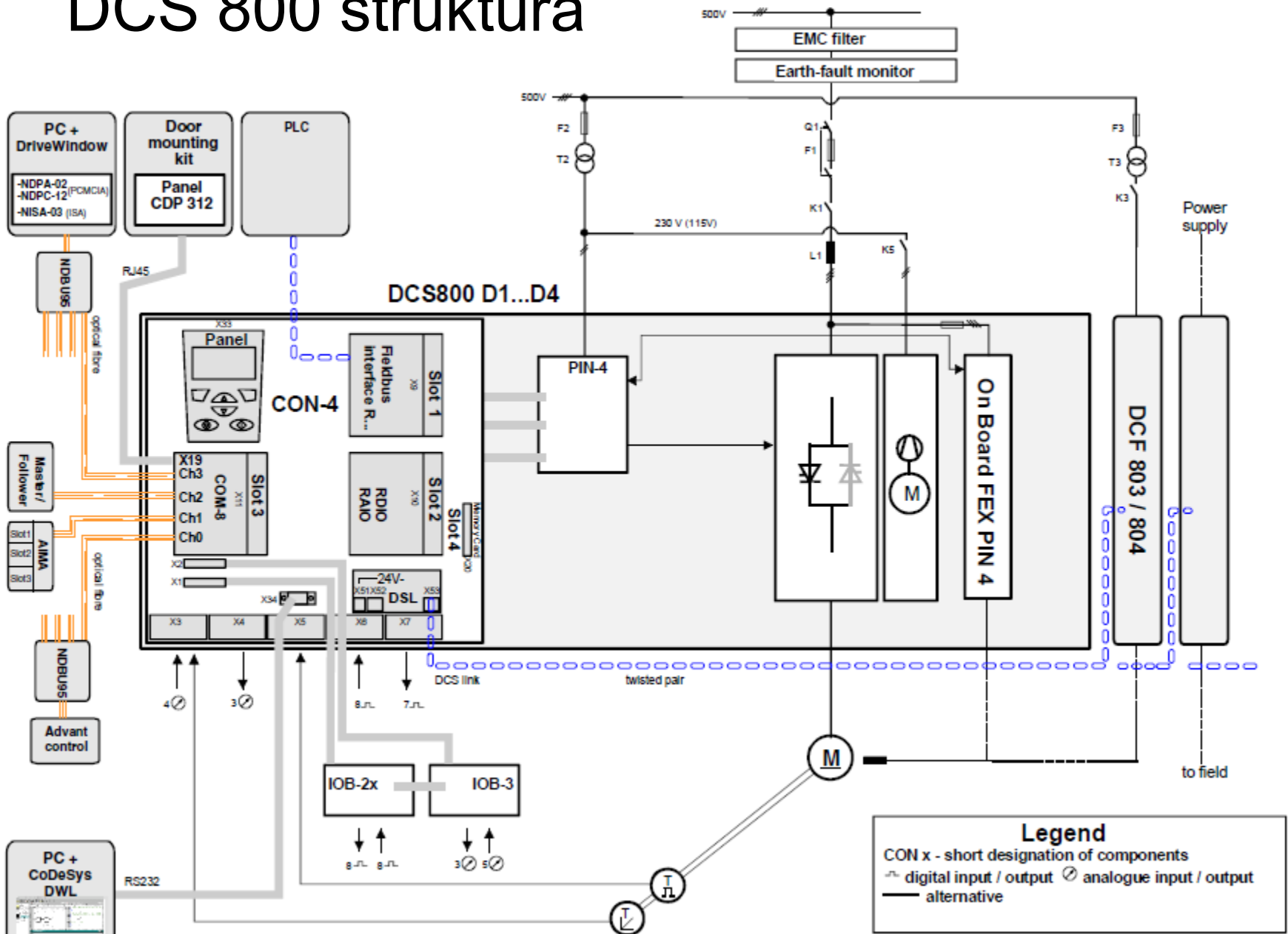
# Logičko kolo

Logičko kolo deluje na blokiranje impulsa mosta koji ne treba da vodi.



Pogoni sa razdeljenim upravljanjem mogu da ostvare bržu promenu znaka struje nego pogoni sa preklopnikom.

# DCS 800 struktura

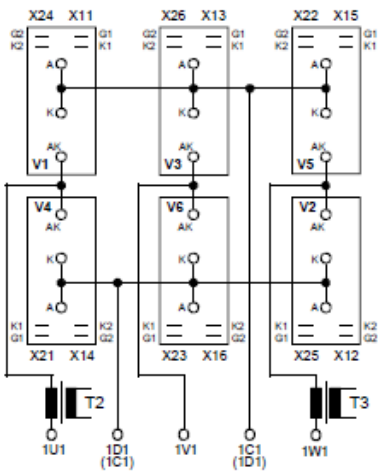


**Armature circuit converter DCS800 D1...D4**  
 400 V and 500 V units with Onboard field exciter  
 600 V units are always without Onboard field exciter

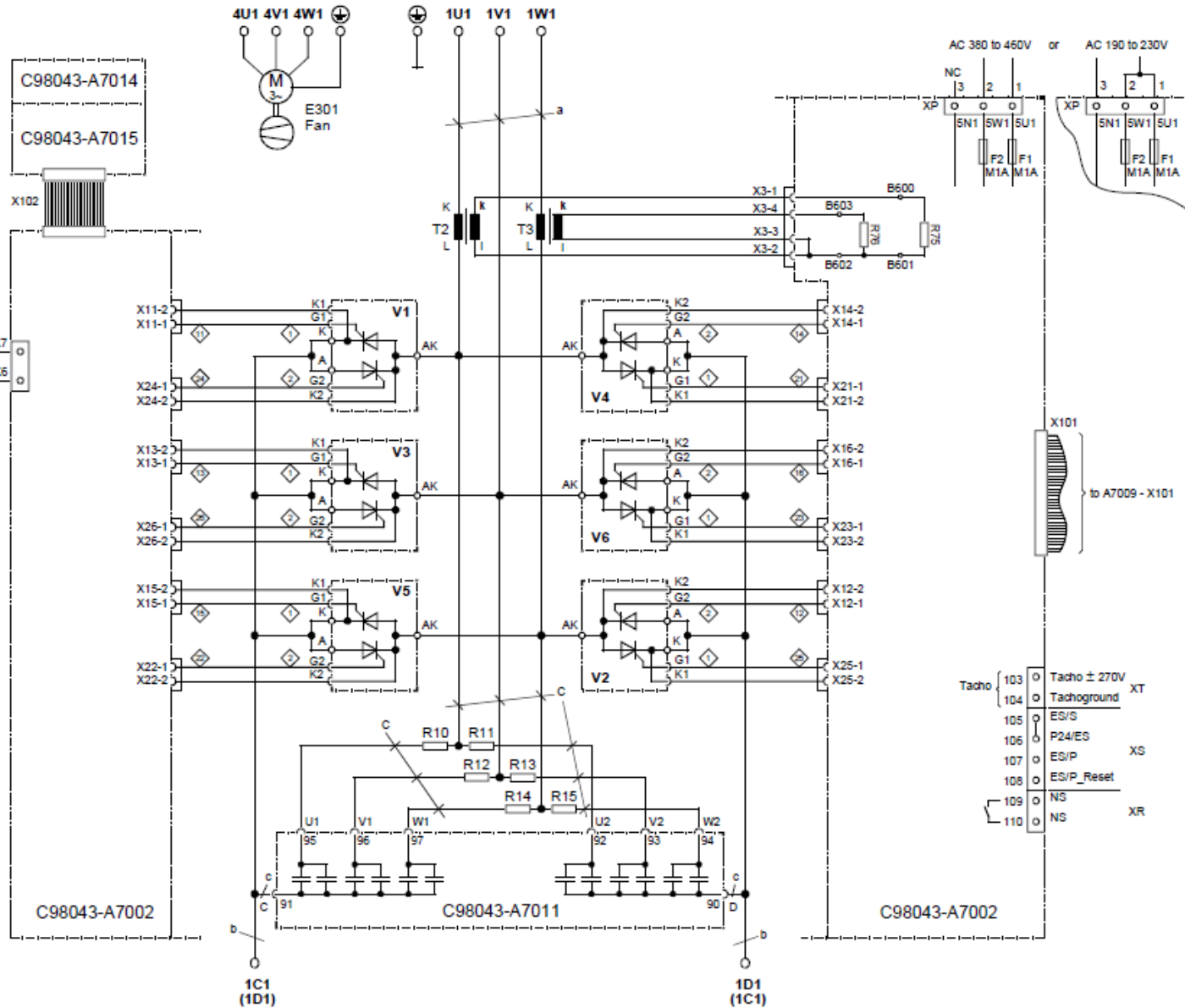
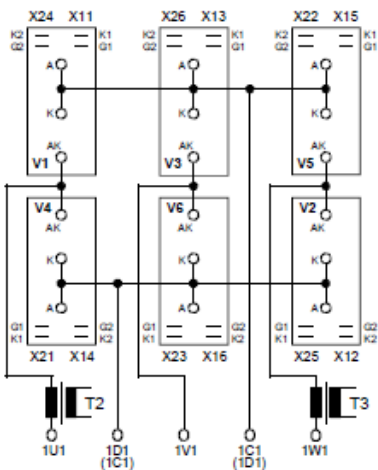
# SIMOREG struktura (energetski deo)

a - copper busbar 20 x 3  
 b - copper busbar 20 x 5  
 c - Raychem 44A0311-20-9  
 All cables are Betatherm 145 1mm<sup>2</sup> unless otherwise designated  
 G (Gate) leads → yellow  
 K (cathode) leads → red  
 ◇ Cables are designated as specified at ends

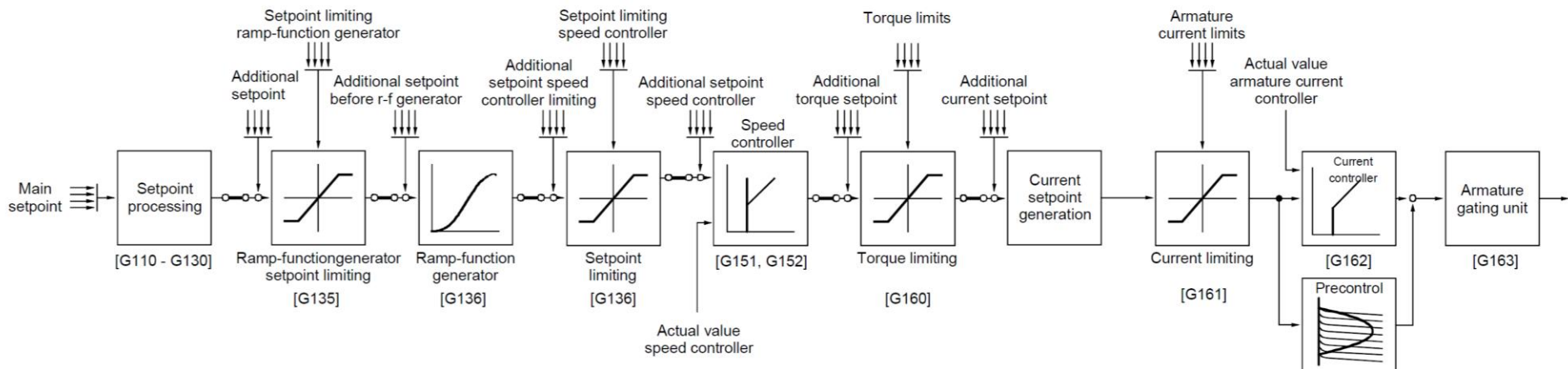
Arrangement of thyristor modules  
 Converters: 400V / 400A



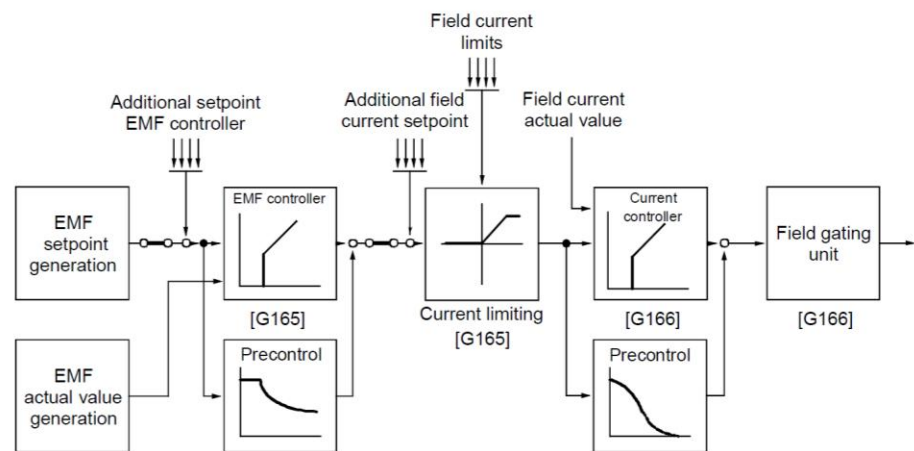
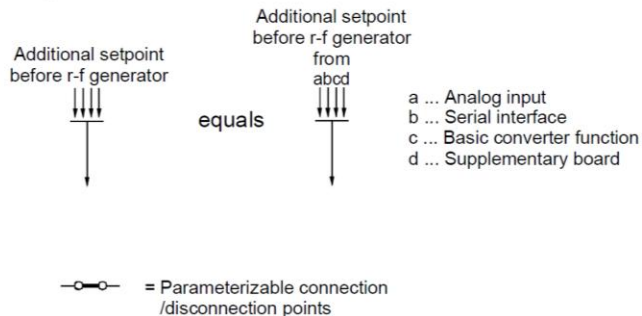
Converters: 575 / 400A



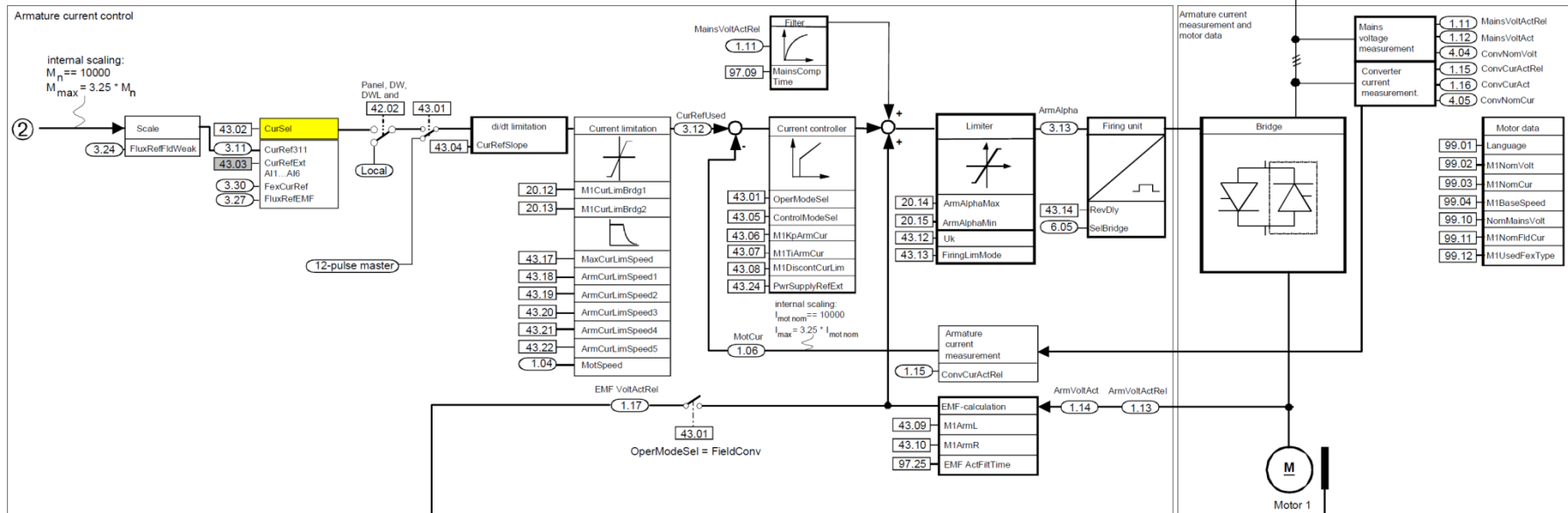
# SIMOREG blok dijagram



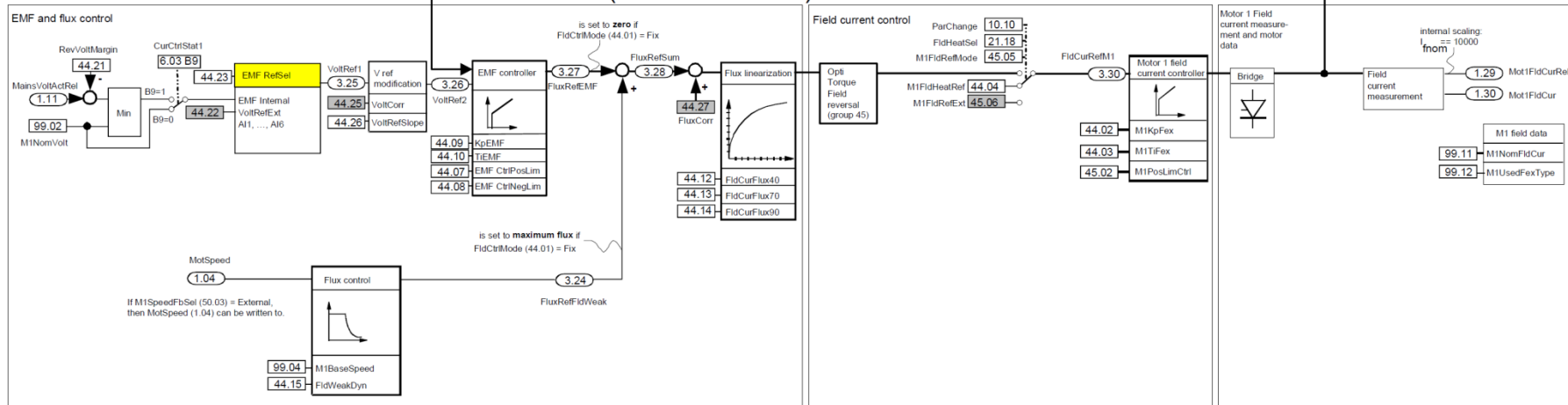
Legend :



# DCS 800 Blok dijagram – regulacija struje



## FIELD CURRENT CONTROL (one field exciter)



# DCS 800 Blok dijagram – upravljanje momentom

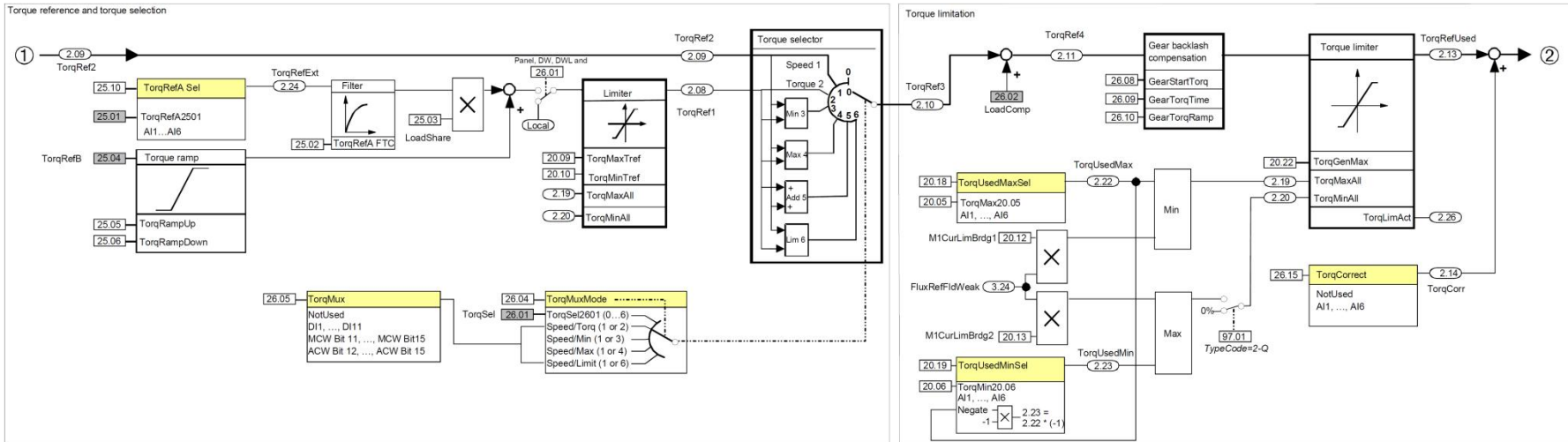
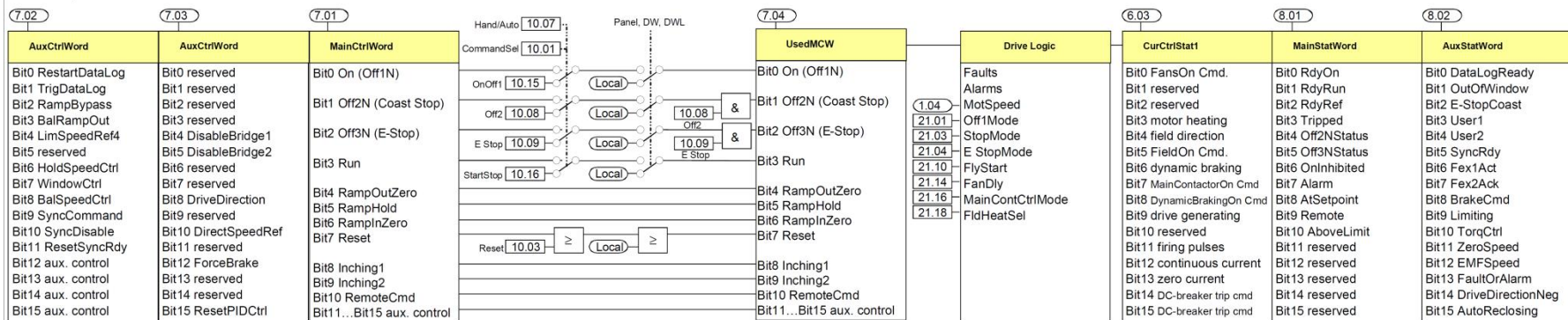
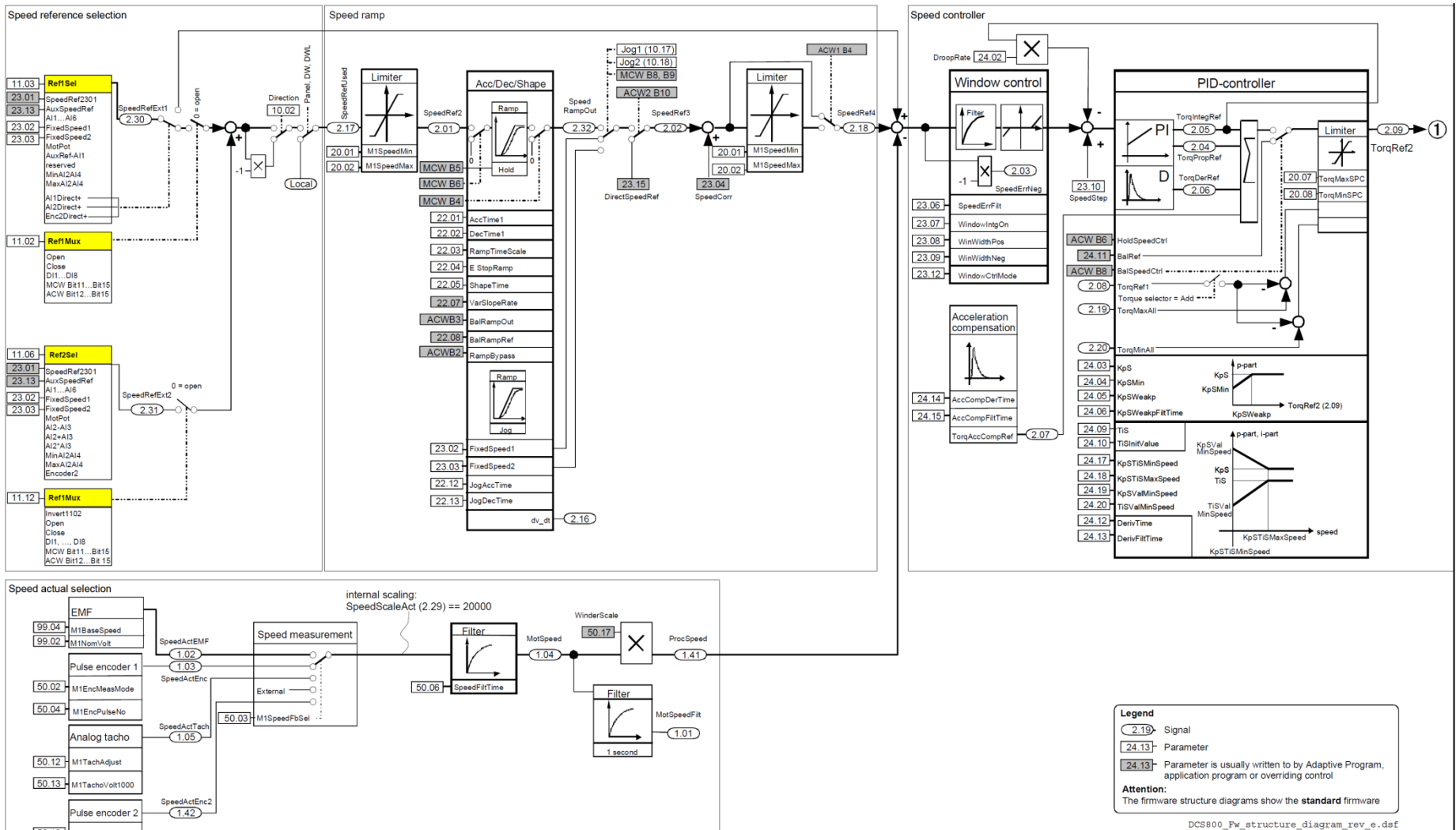


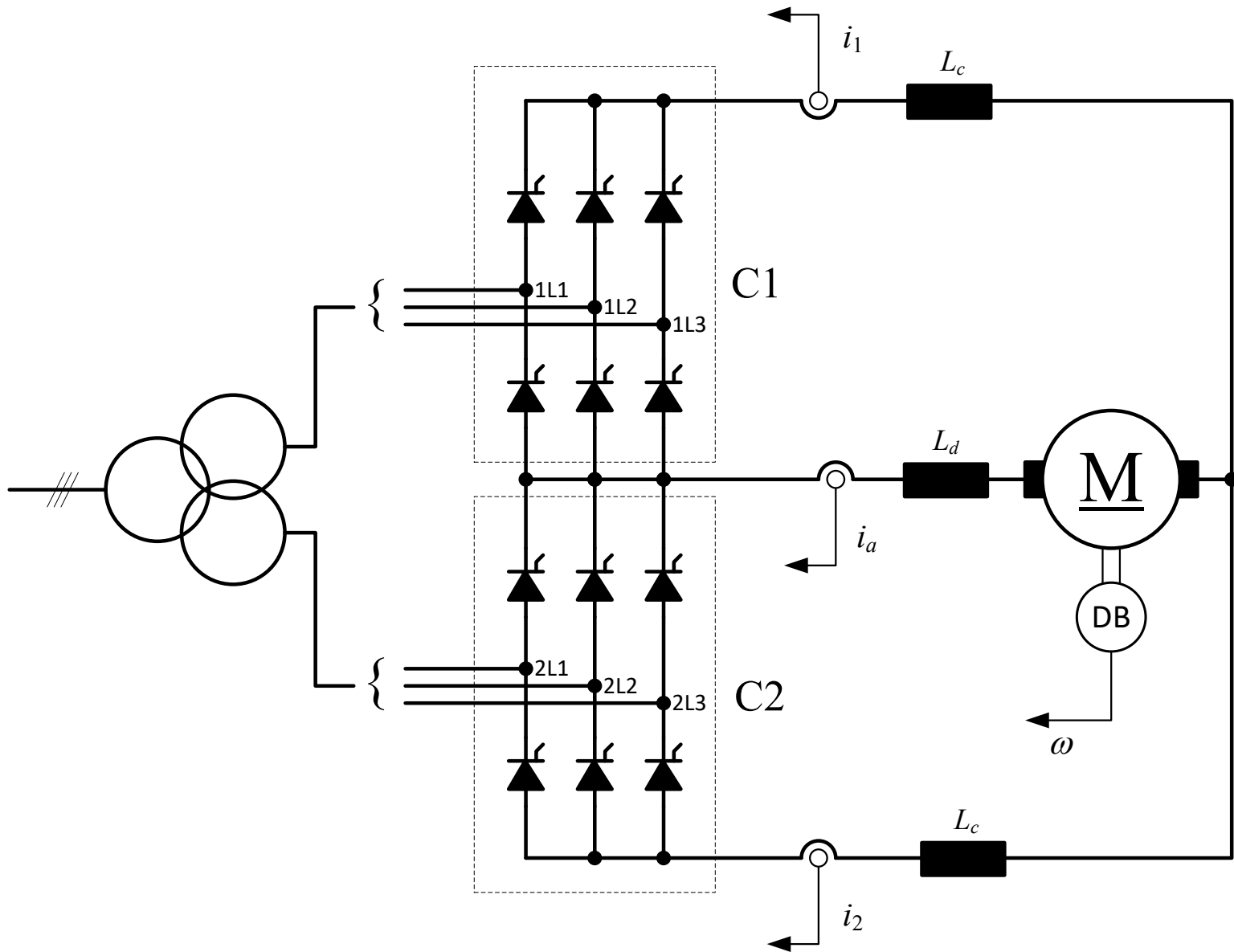
ABB Drive profile control



# DCS 800 Blok dijagram – regulacija brzine

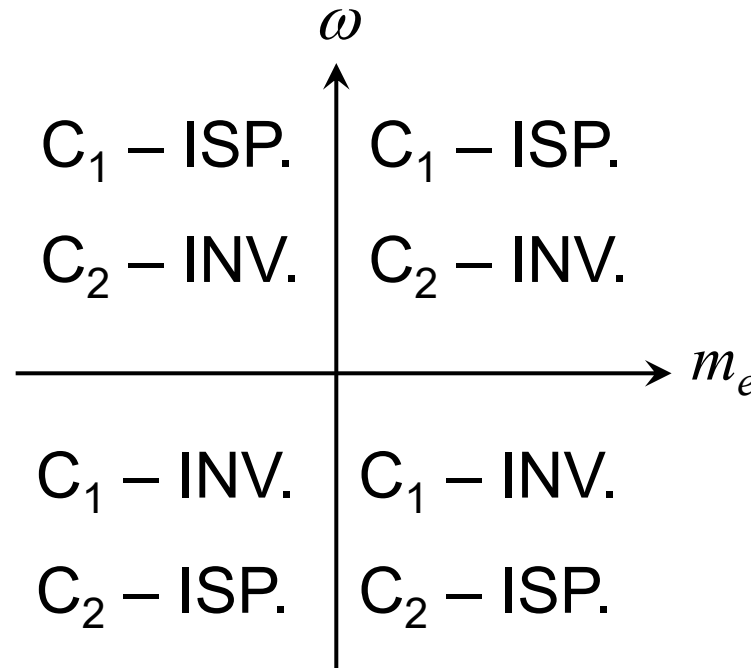


# Četvoro-kvadrantni rad sa kružnom strujom



# Četvoro-kvadrantni rad sa kružnom strujom (saglasno upravljanje)

Koristi se za ostvarivanje brzih reversa  
(promene znaka) momenta.

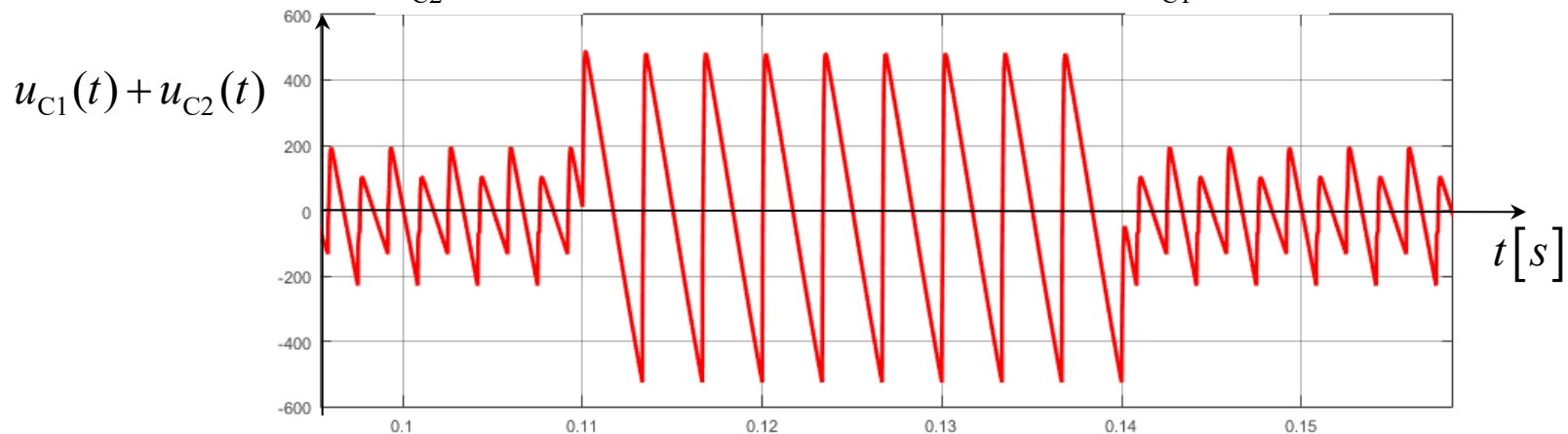
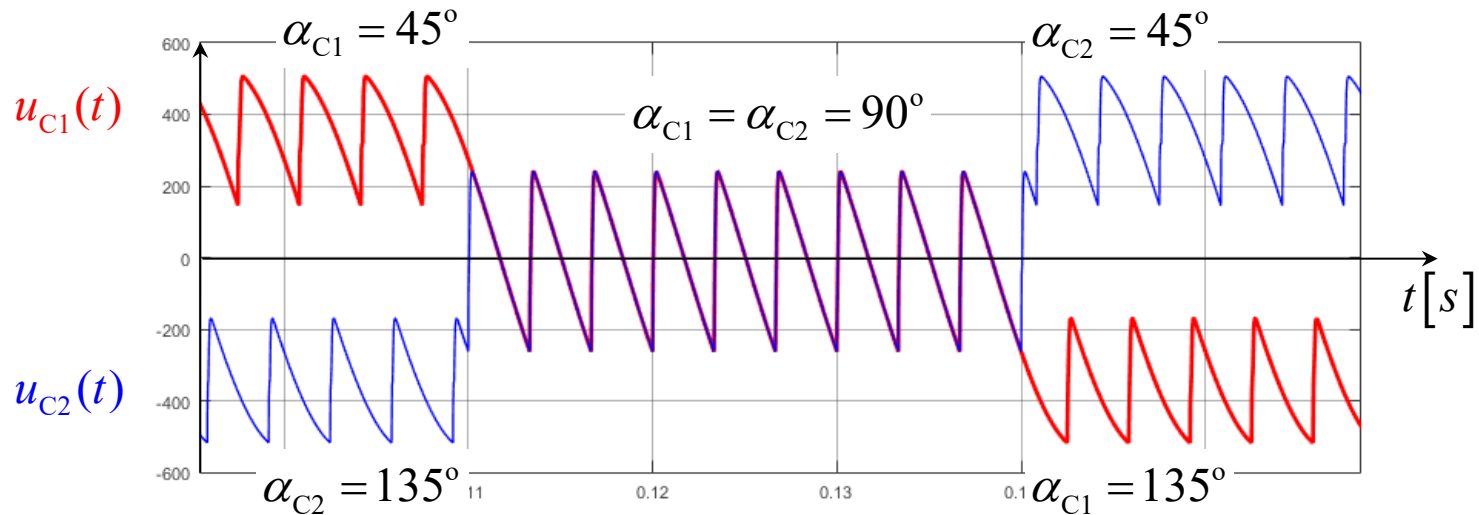


$$\alpha_1 + \alpha_2 = 180^\circ$$

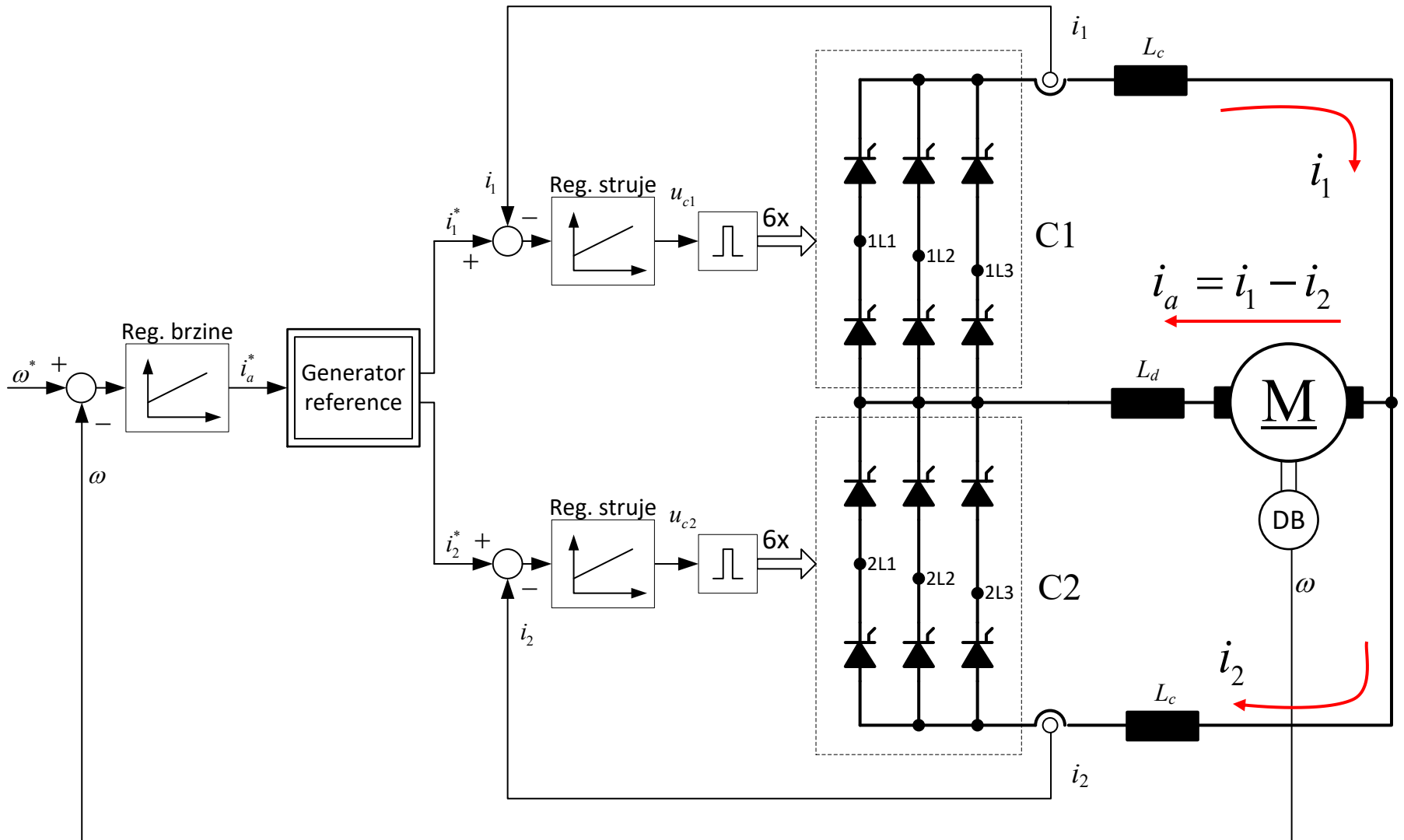
# Dijagram trenutnih vrednosti napona

$$|U_{C1}(\alpha_1)| = |U_{C2}(\alpha_2)| \quad u_{C1}(t) \neq u_{C2}(t) \quad \leftarrow \text{kružna struja}$$

$$\text{samo za } \alpha_{C1} = \alpha_{C2} = 90^\circ \Rightarrow u_{C1}(t) = u_{C2}(t)$$



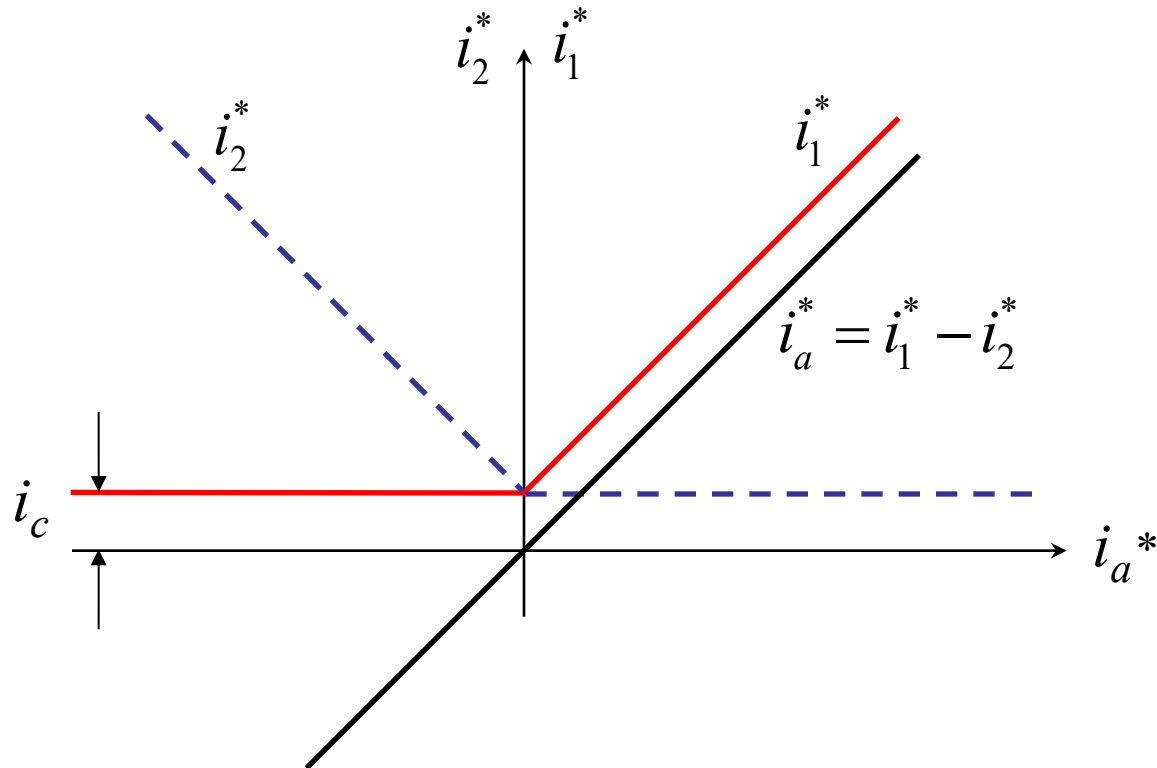
# Kontrola kružne struje



# Generator referentnih struja $i_1^*$ i $i_2^*$

$i_c$  – cirkulaciona (kružna) struja

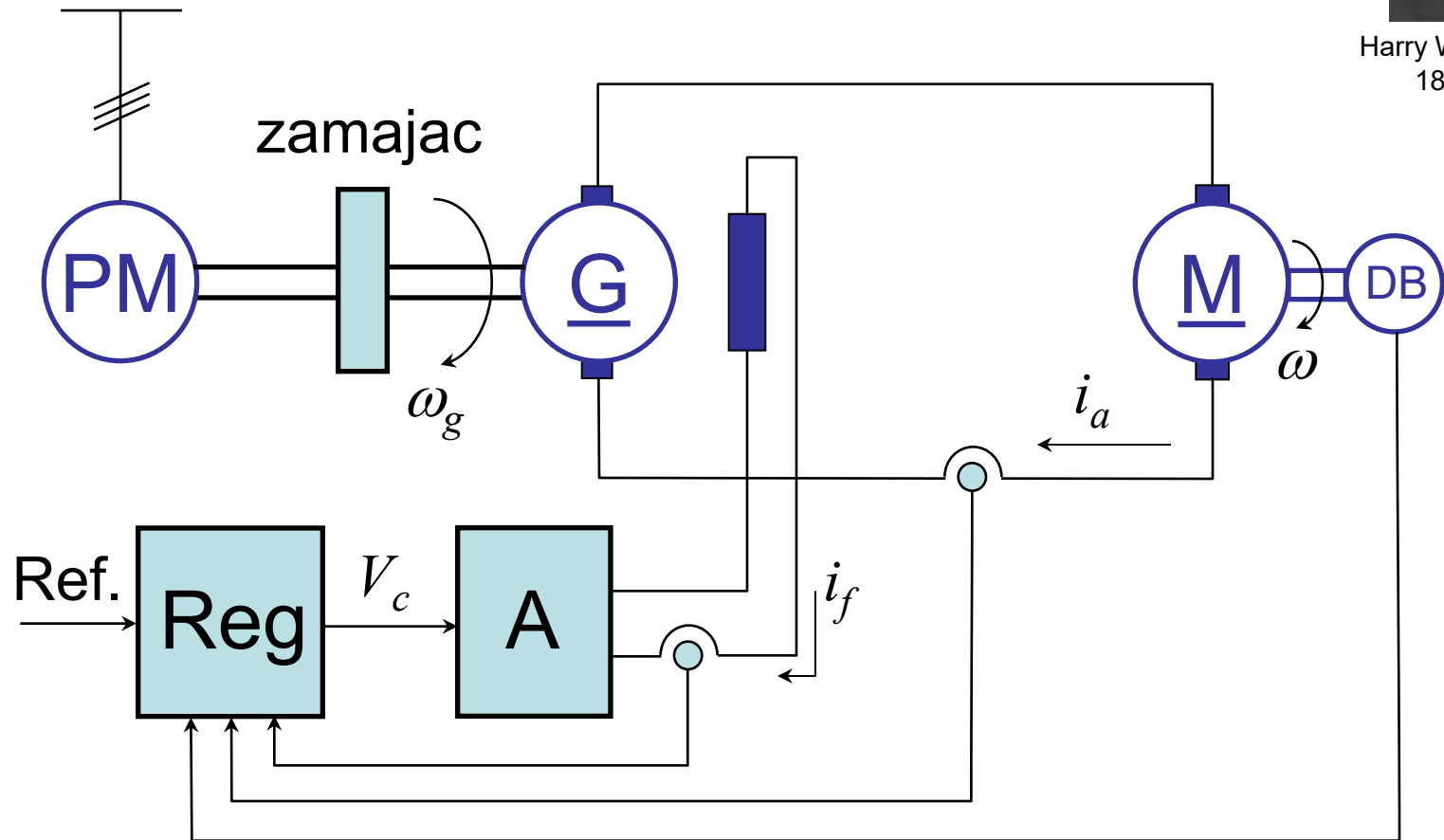
Po vrednosti, kružna struja bi trebalo da bude minimalna, ali da se tiristori odgovarajućeg mosta održavaju u provodnom stanju.



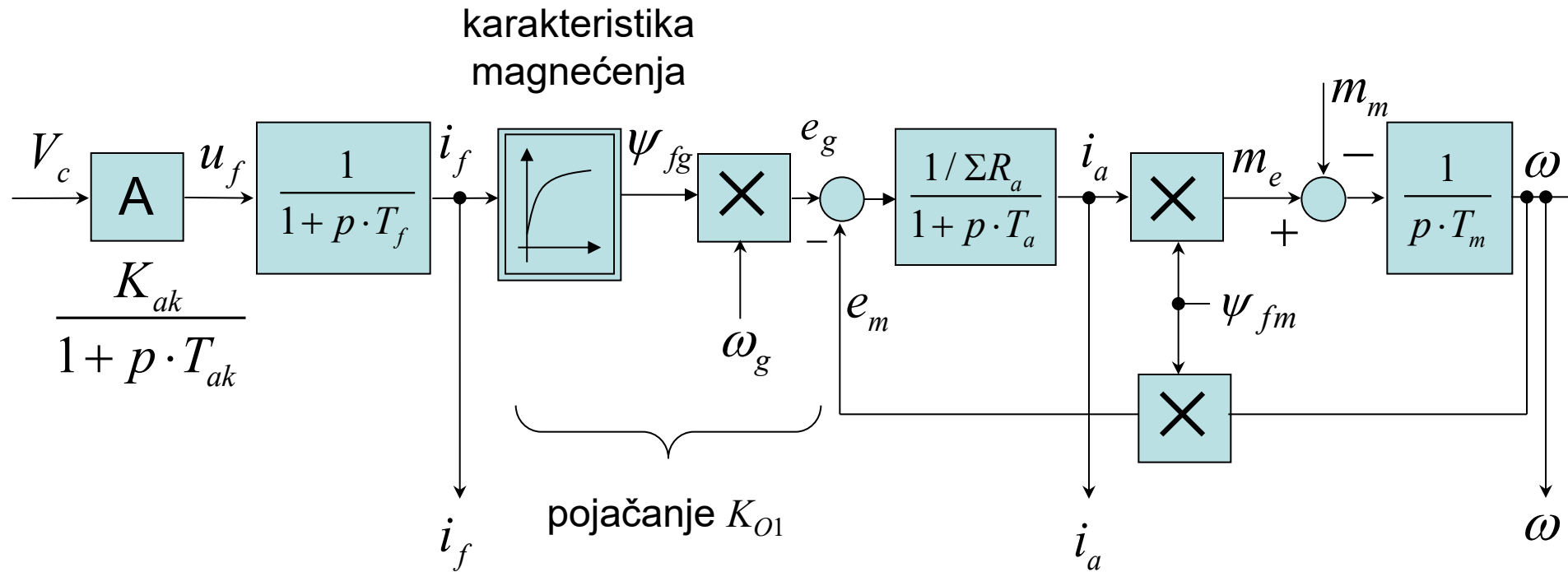
# Vard Leonardova grupa



Harry Ward Leonard  
1861-1915.



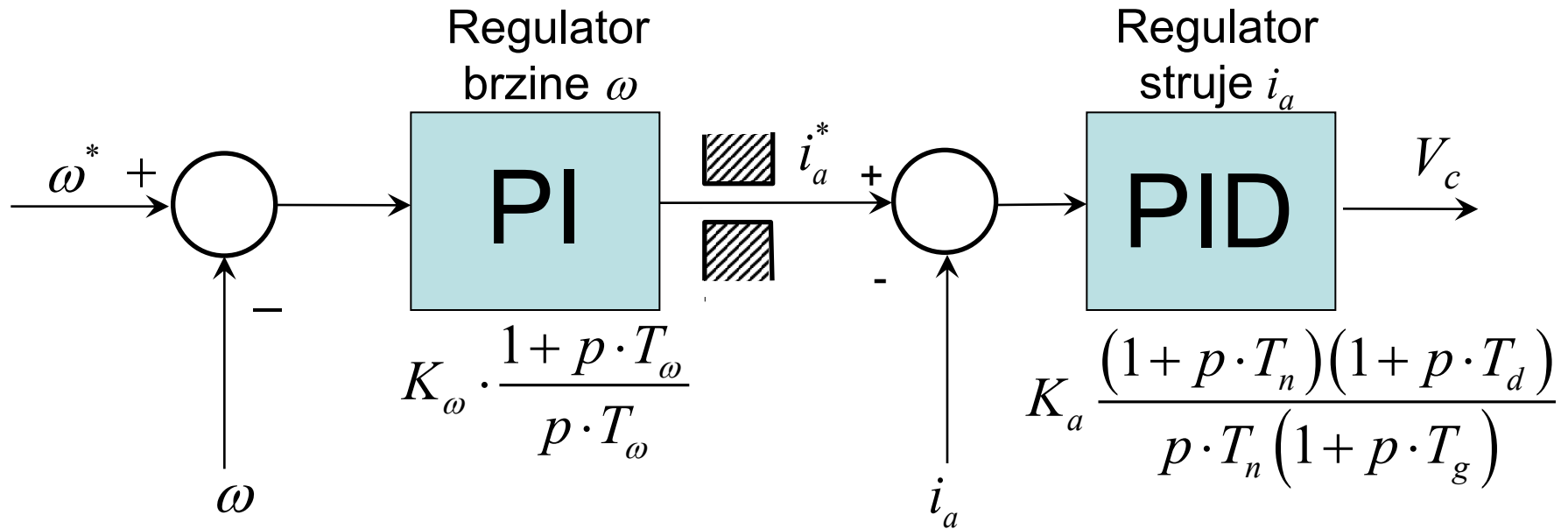
# Vard Leonardova grupa (blok dijagram)



$$T_a = \frac{2 \cdot L_a}{2 \cdot R_a} \quad T_f > T_a > T_{ak}$$

# Vard Leonardova grupa

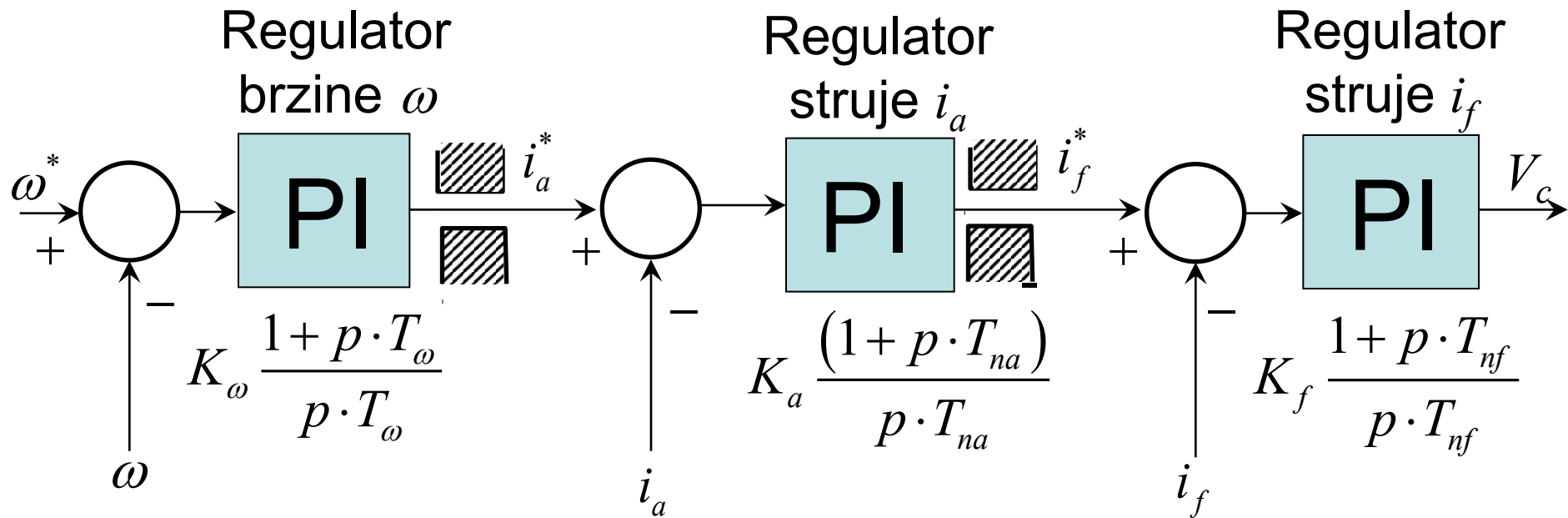
## Regulator: PI + PID



REG  $i_a$ :  $(T_n = T_f \quad T_d = T_a) \Rightarrow |F(j\omega)|$  drugog reda.

REG  $\omega$ :  $\Rightarrow |F(j\omega)|$  trećeg reda.

# Vard Leonardova grupa regulator (PI + PI + PI)



REG  $i_f$ :  $(T_{nf} = T_f) \Rightarrow |F(j\omega)|$  drugog reda.

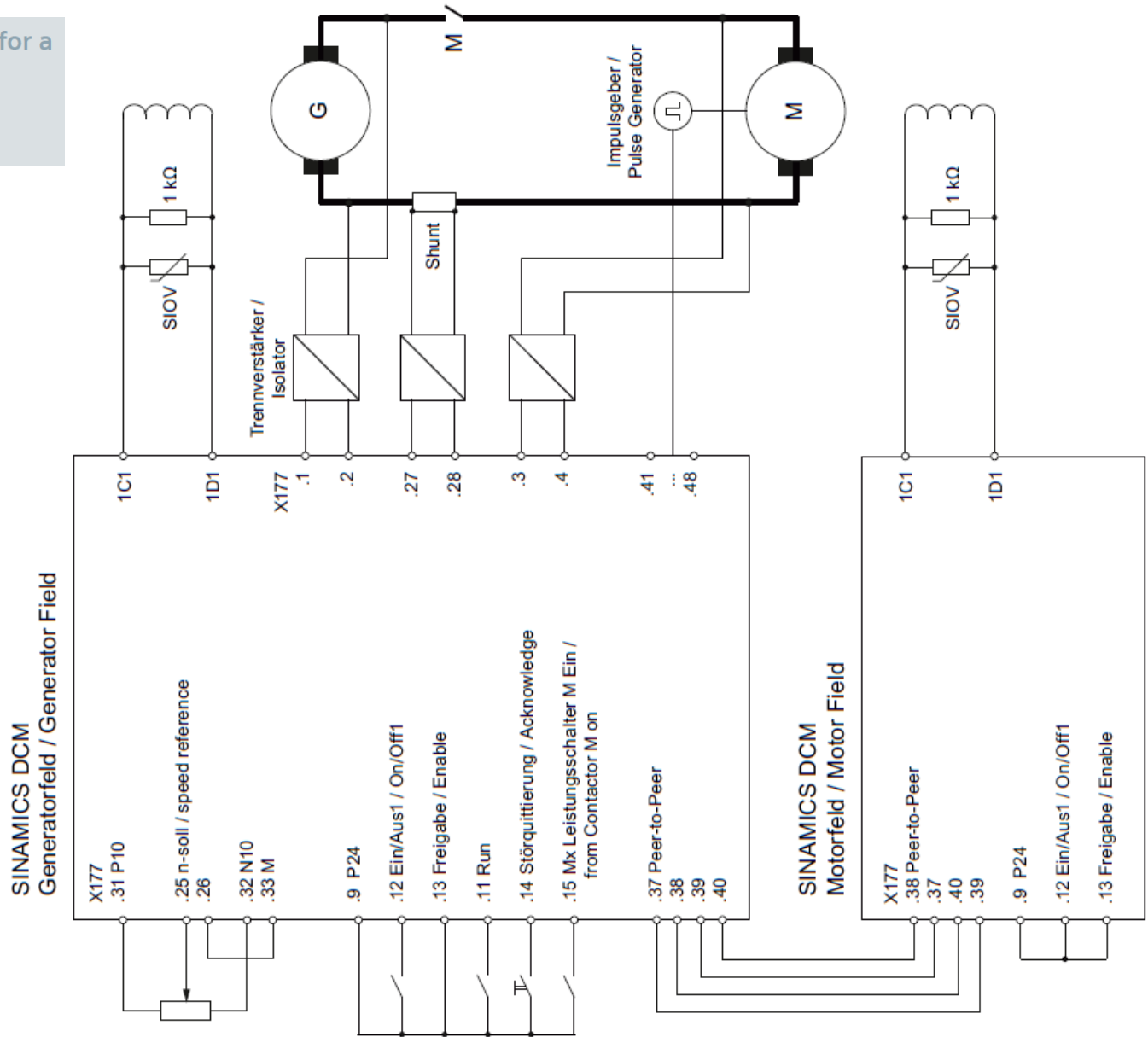
REG  $i_a$ :  $(T_{na} = T_a) \Rightarrow |F(j\omega)|$  drugog reda.

REG  $\omega$ :  $\Rightarrow |F(j\omega)|$  trećeg reda.

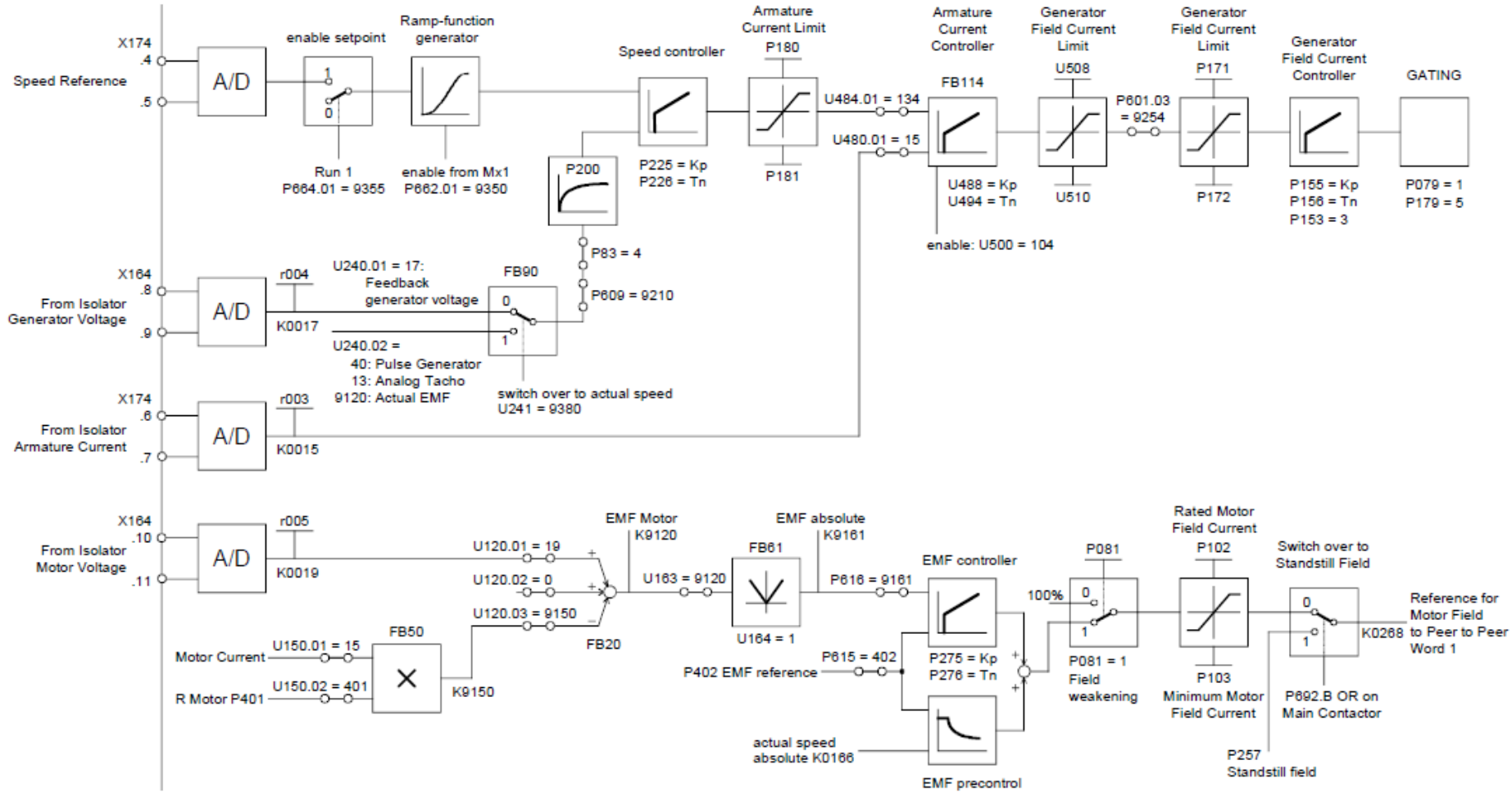
# Vard Leonardova grupa

Closed-loop control application for a Ward-Leonard block

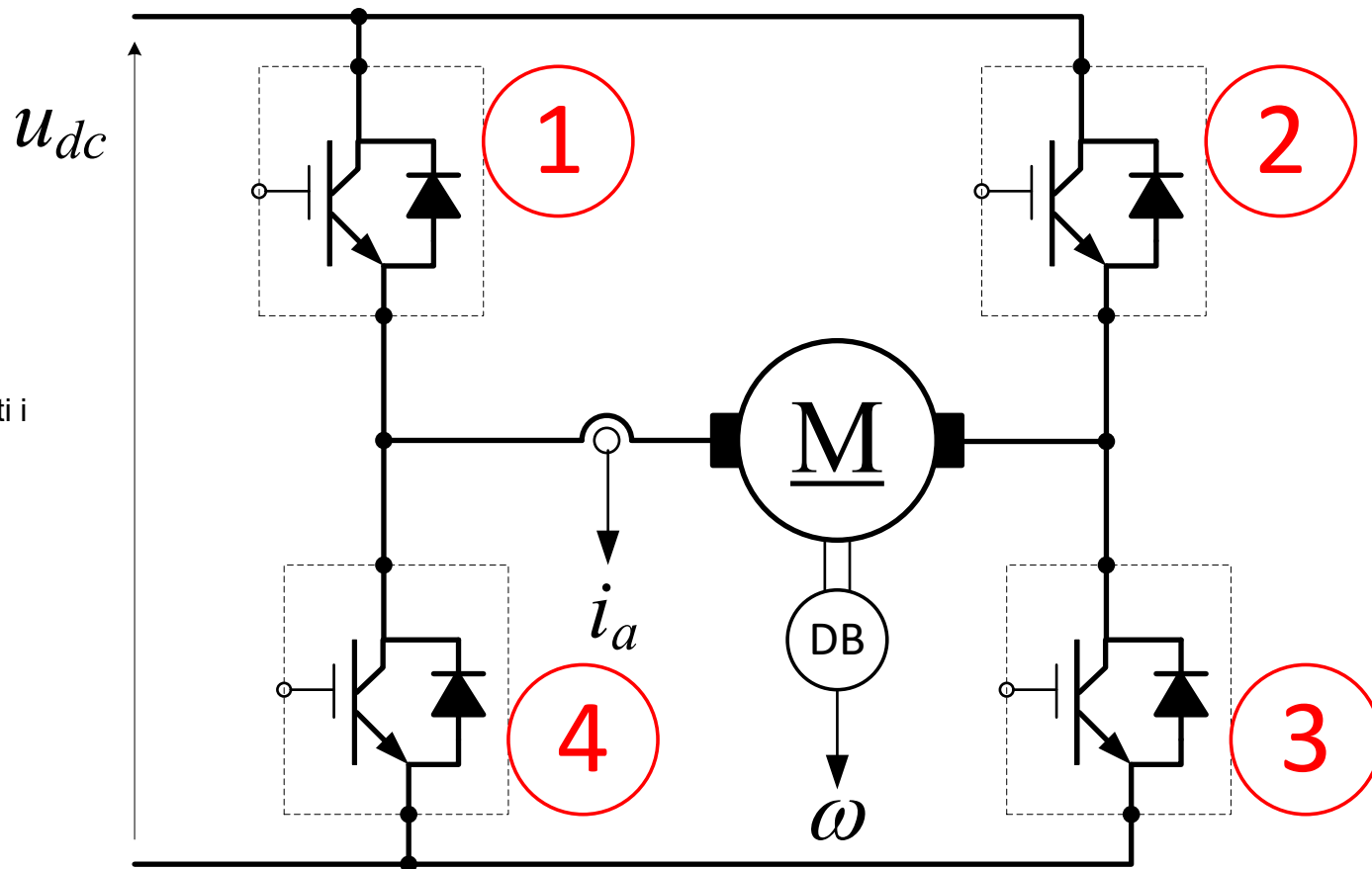
Edition 02 - 06/2013



# Vard Leonardova grupa



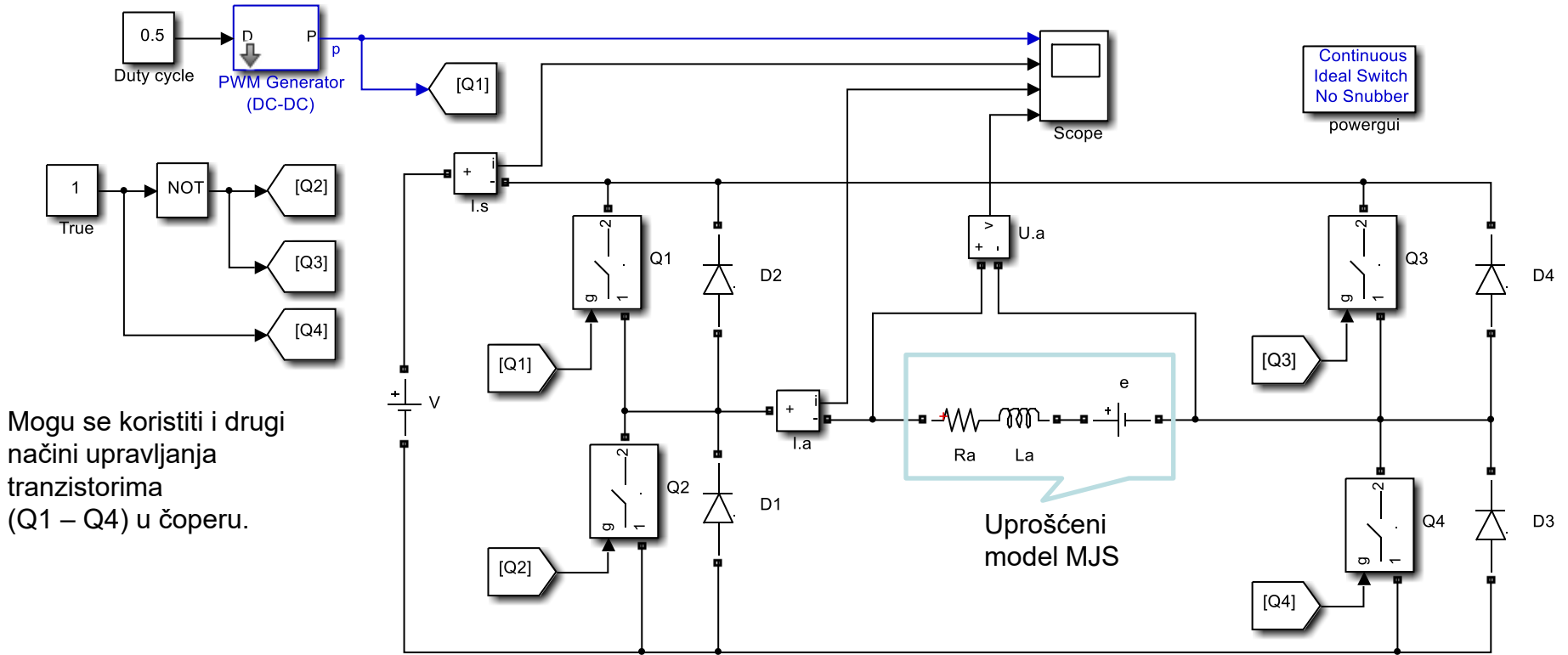
# Četvoro-kvadrantni čoper



Označavanje  
tranzistora može biti i  
drugačije:

Q1	Q3
Q2	Q4

# ČOPER KLASSE E



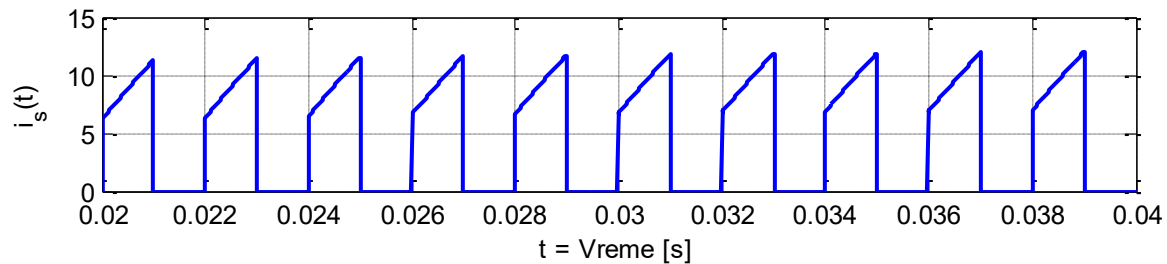
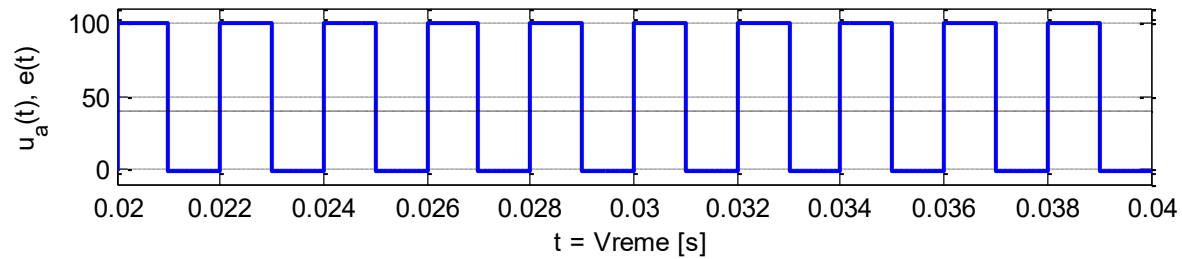
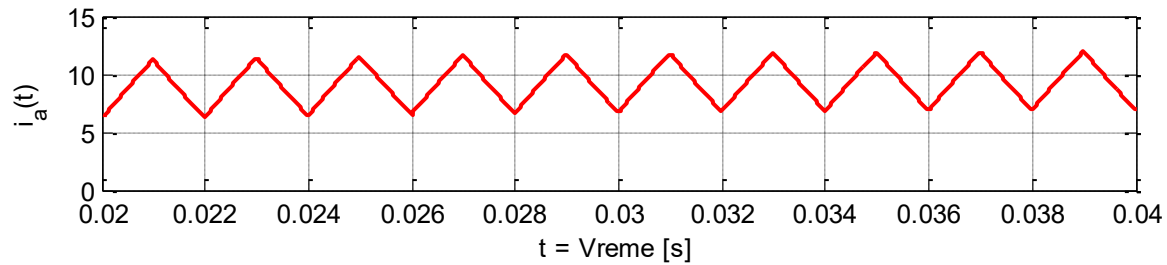
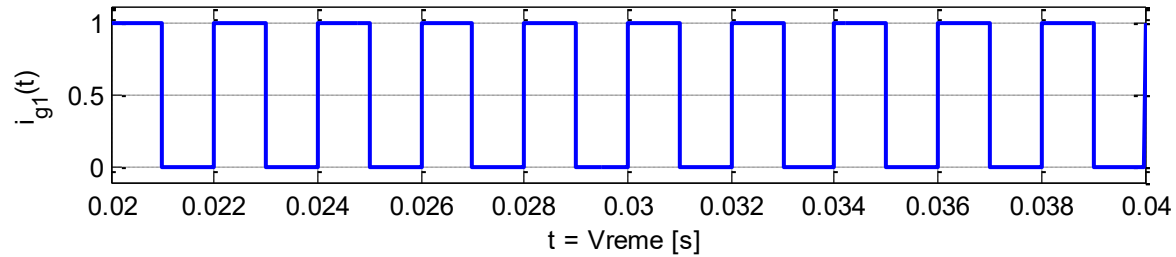
$$V = 100V, e = 40V$$

$$R_a = 1\Omega, L_a = 10mH$$

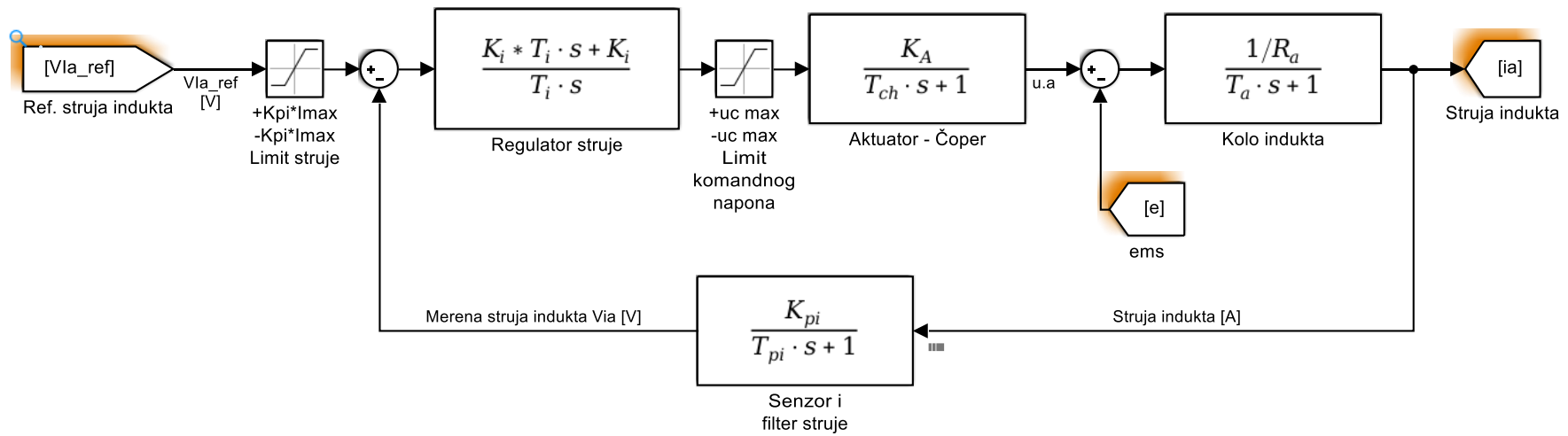
$$T_p = 0,002s \quad F_p = 500Hz$$

# Čoper klase E

## Režim rada sa neprekidnom strujom



# Blok dijagram regulacione petlje po struji indukta sa PI regulatorom



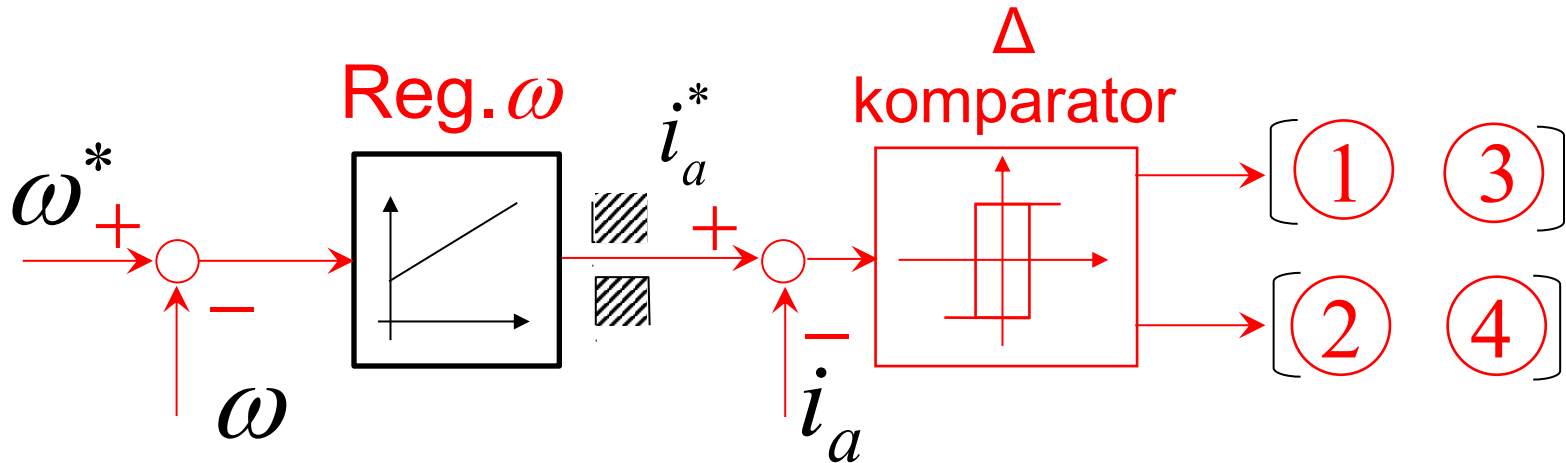
$K_{pi}$  – pojačanje senzora struje

$T_{pi}$  – vremenska konstanta filtera u povratnoj vezi

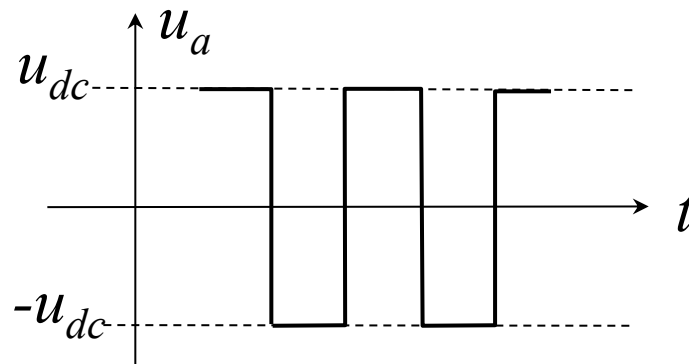
PI regulator struje:

$$\frac{K_i \cdot T_i \cdot s + K_i}{T_i \cdot s} = K_i \cdot \left( 1 + \frac{1}{T_i \cdot s} \right) = K_i \frac{T_i \cdot s + 1}{T_i \cdot s} = K_i \frac{1 + T_i \cdot p}{T_i \cdot p}$$

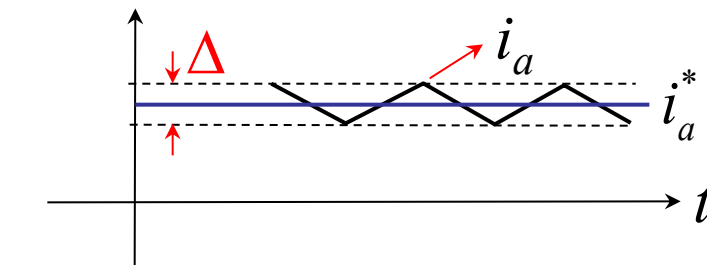
# Struktura regulatora sa histerezisnim regulatorom struje indukta



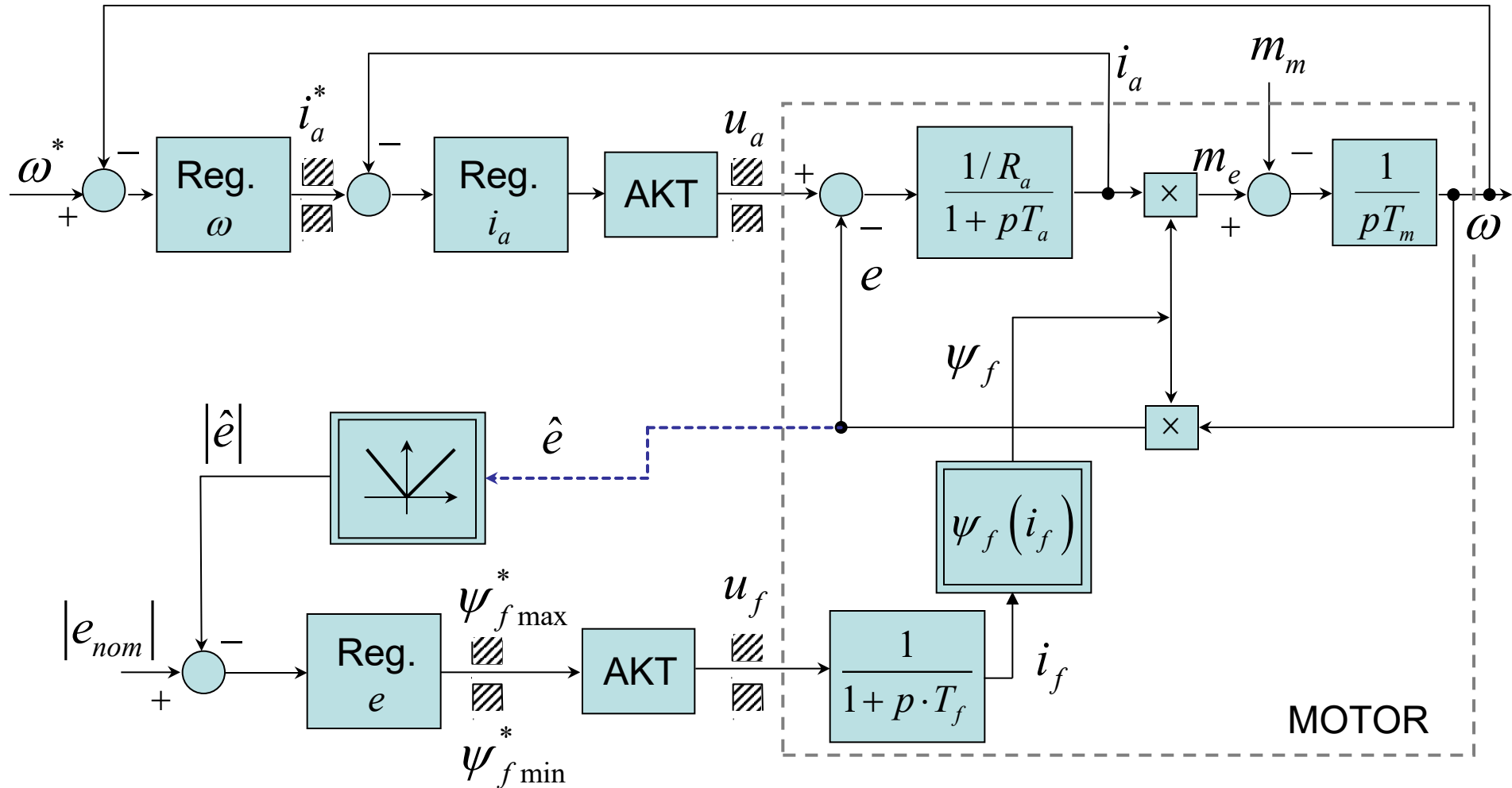
Trenutne vrednosti  
napona



i  
struje motora

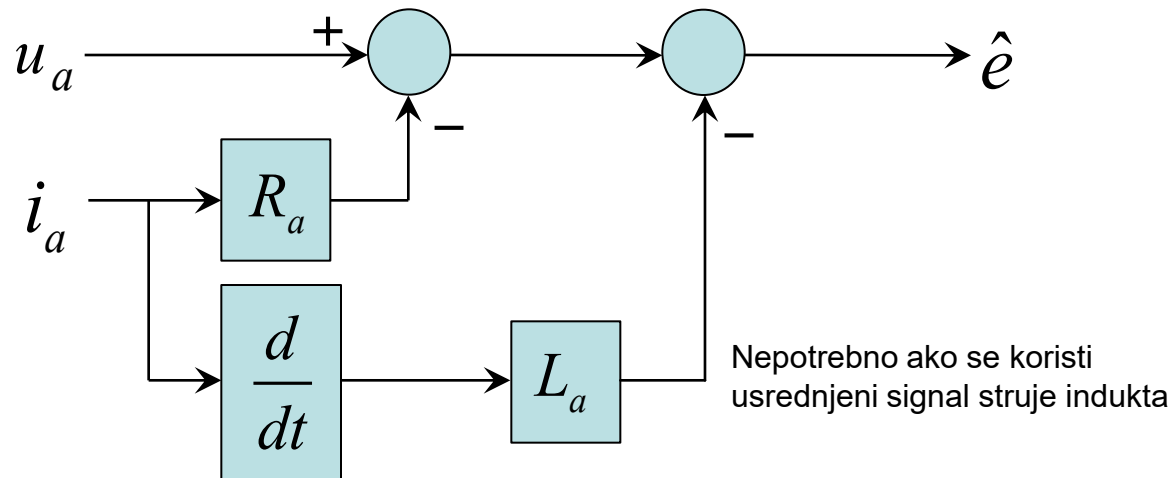


# Upravljanje motorom kod regulacije brzine u proširenom opsegu brzina (sa slabljenjem polja)

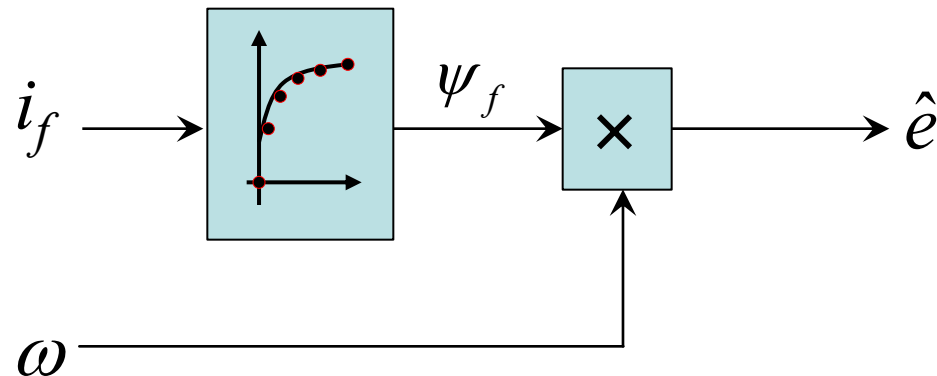


Merenje *elektromotorne sile nije moguće*.  
Izračunava se na osnovu merenja dostupnih veličina.

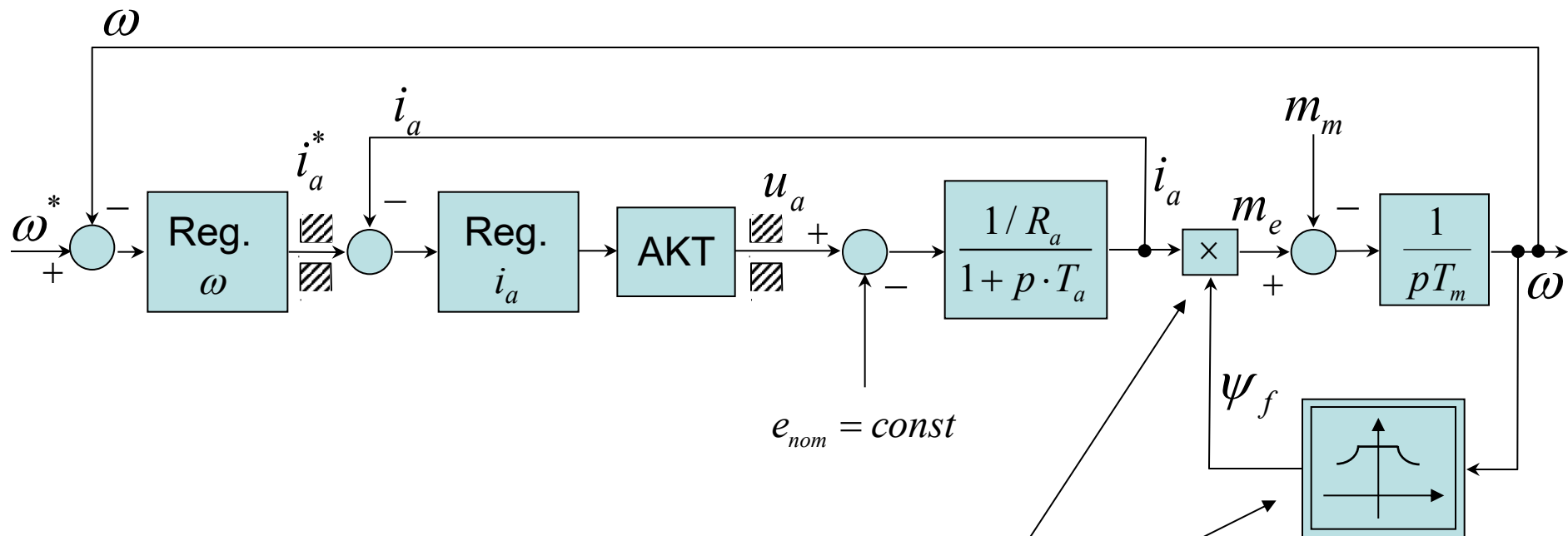
Prvi način: merenjem struje i napona indukta



Drugi način: merenjem struje pobude i brzine



# Blok dijagram sistema pri brzini većoj od nominalne



Nelinearno