

# VEKTORSKI UPRAVLJAN ASINHRONI MOTOR

$$m_e \sim \vec{i}_s \times \vec{\varphi}_r$$

# Osobine pogona sa vektorskim upravljanjem

- Cilj (zadatak) je nezavisno upravljanje fluksom i momentom asinhronog motora
- Pogon mora imati energetska pretvarač – aktuator. U zavisnosti od tipa aktuatora, zavisi i način realizacije upravljačkog sistema.
- Pogon mora imati regulaciju struje, zahteva se promena učestanosti, amplitude i položaja prostornog vektora struje.

# Prva publikacija

## Indirektno vektorsko upravljanje



TECHNISCHE  
UNIVERSITÄT  
DARMSTADT

K. Hasse,

“O dinamici brzinski regulisanog  
pogona sa asinhronom mašinom  
sa kratkospojenim rotorom  
napajanom iz pretvarača”

Doktorska disertacija na Visokoj  
tehničkoj školi Darmstadt, 1969.

K. Hasse,

“Zur Dynamik

drehzahl geregelter Antriebe  
mit stromrichter gespeisten  
Asynchronkurzschlußläufer  
maschinen,”

Ph.D. dissertation,

TH Darmstadt,

**1969.**

By Felix Blaschke

When rotating-field machines are employed as drive motors, the question of torque generation and control requires special consideration. It is, for instance, possible to use the vector of the stator voltage or the vector of the stator current as the manipulated variable for the torque, depending on whether the static converter supplying the motor provides a variable voltage or a variable current. This paper describes the principle of field orientation – a new closed-loop control method for rotating-field machines [1 to 4] – by way of reference to an induction motor. It is shown how the manipulated variables must be influenced to provide instantaneous and well-damped adjustment of the torque independently of the inherent characteristics of an induction motor.

**Field orientation with current control**

The principle of field orientation can best be explained by reference to the characteristics of a d.c. motor. Fig. 1 shows a d.c. motor of the non-salient-pole type. Arranged in the stator perpendicular to each other are two windings 1 and 2. Owing to the action of the commutator, the rotating armature winding 3 produces the effect of a stationary winding. If a current  $i_1$  is passed through field winding 1, a magnetic field  $\Psi$  builds up in the motor (Fig. 2, left). For the generation of a torque, a current  $i_2$  must also be passed through the armature winding. The armature current and field now set up forces in the directions shown. Since the axis of the armature winding is perpendicular to the field, the forces are applied with maximum leverage to the shaft. Hence, this position of the armature winding is the most favourable one for torque generation. The armature winding also builds up a field that is superimposed on the original field and is perpendicular to it. This effect is undesirable, since it turns the field out of the optimal position. For this reason, the armature field is compensated by a compensating winding 2 arranged in the stator in the same plane as the armature winding and carrying the same current, but in the opposite direction ( $i_2 = -i_3$ ). This stator winding and the field produce in the stator a reaction torque which acts against the armature. The currents and the field may vector diagram\* shown on the right machine, therefore, current  $i_1$  forms  $i_2$  and  $i_3$ , together with the field

In an induction motor, the place of the commutator-fed armature winding is taken by a short-circuited winding which may, for instance, consist of conductor bars distributed uniformly round the periphery and connected by two short-circuiting rings at the ends (Fig. 3). The current required in this winding for the setting up of a torque can only be generated by induction, i.e. by field change. Again a field is set up by a current  $i_1$  in winding 1. If now a current  $i_2$  is suddenly

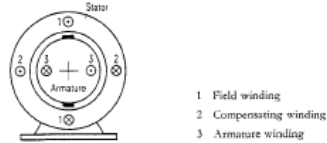


Fig. 1 Representation of a d.c. motor

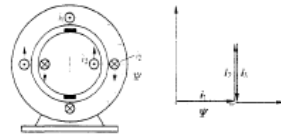


Fig. 2 State of field and currents in a d.c. motor

Dipl.-Ing. Felix Blaschke, Siemens Aktiengesellschaft, Measurement and Process Engineering D

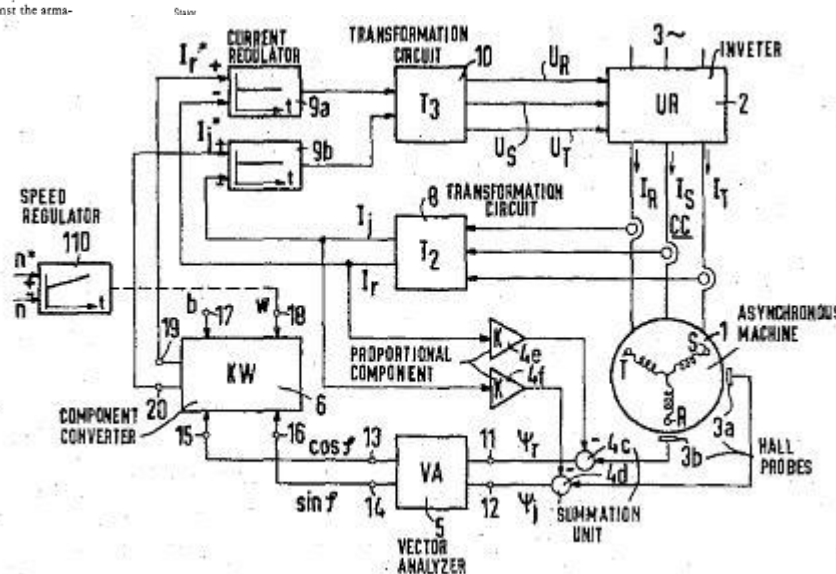
\* For a definition of space vectors due to [5]. Space vectors and matrices are denoted by boldface letters.

# Prva publikacija Direktno vektorsko upravljanje

F. Blaschke,

"The principle of field orientation as applied to the new TRANSVEKTOR closed loop control system for rotating field machines,"  
Siemens Rev., vol. 34,  
pp. 217-220,

**1972.**



# Dinamički model asinhronog motora

Sinhrono rotirajući referentni sistem

$$\omega_{rs} = \omega_s$$

$$p = \frac{d}{dt}$$

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$$u_{qs} = R_s \cdot i_{qs} + p\varphi_{qs} + \omega_s \cdot \varphi_{ds} \quad (1)$$

$$u_{ds} = R_s \cdot i_{ds} + p\varphi_{ds} - \omega_s \cdot \varphi_{qs} \quad (2)$$

$$0 = R'_r \cdot i'_{qr} + p\varphi'_{qr} + (\omega_s - \omega) \cdot \varphi'_{dr} \quad (3)$$

$$0 = R'_r \cdot i'_{dr} + p\varphi'_{dr} - (\omega_s - \omega) \cdot \varphi'_{qr} \quad (4)$$

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$$\varphi_{qs} = L_s \cdot i_{qs} + M \cdot i'_{qr} \quad (5)$$

$$\Rightarrow L_s = M + \lambda_s$$

$$\varphi_{ds} = L_s \cdot i_{ds} + M \cdot i'_{dr} \quad (6)$$

$$\varphi'_{qr} = L'_r \cdot i'_{qr} + M \cdot i_{qs} \quad (7)$$

$$\Rightarrow L'_r = M + \lambda'_r$$

$$\varphi'_{dr} = L'_r \cdot i'_{dr} + M \cdot i_{ds} \quad (8)$$

---

$$m_e = \frac{3}{2} \cdot P \cdot \frac{M}{L'_r} \cdot (i_{qs} \cdot \varphi'_{dr} - i_{ds} \cdot \varphi'_{qr}) \quad (9)$$

Koordinatni sistem se postavi tako da u svakom trenutku važi:  $\varphi'_{qr} = 0$

$$p\varphi'_{qr} = \frac{d\varphi'_{qr}}{dt} = 0$$

$$u_{qs} = R_s \cdot i_{qs} + p\varphi_{qs} + \omega_s \cdot \varphi_{ds} \quad (1)$$

$$u_{ds} = R_s \cdot i_{ds} + p\varphi_{ds} - \omega_s \cdot \varphi_{qs} \quad (2)$$

$$0 = R'_r \cdot i'_{qr} + \mathbf{0} + \omega_r \cdot \varphi'_{dr} \quad (3)$$

$$\Rightarrow \omega_r = \omega_s - \omega$$

$$0 = R'_r \cdot i'_{dr} + p\varphi'_{dr} - \mathbf{0} \quad (4)$$

$$\varphi_{qs} = L_s \cdot i_{qs} + M \cdot i'_{qr} \quad (5)$$

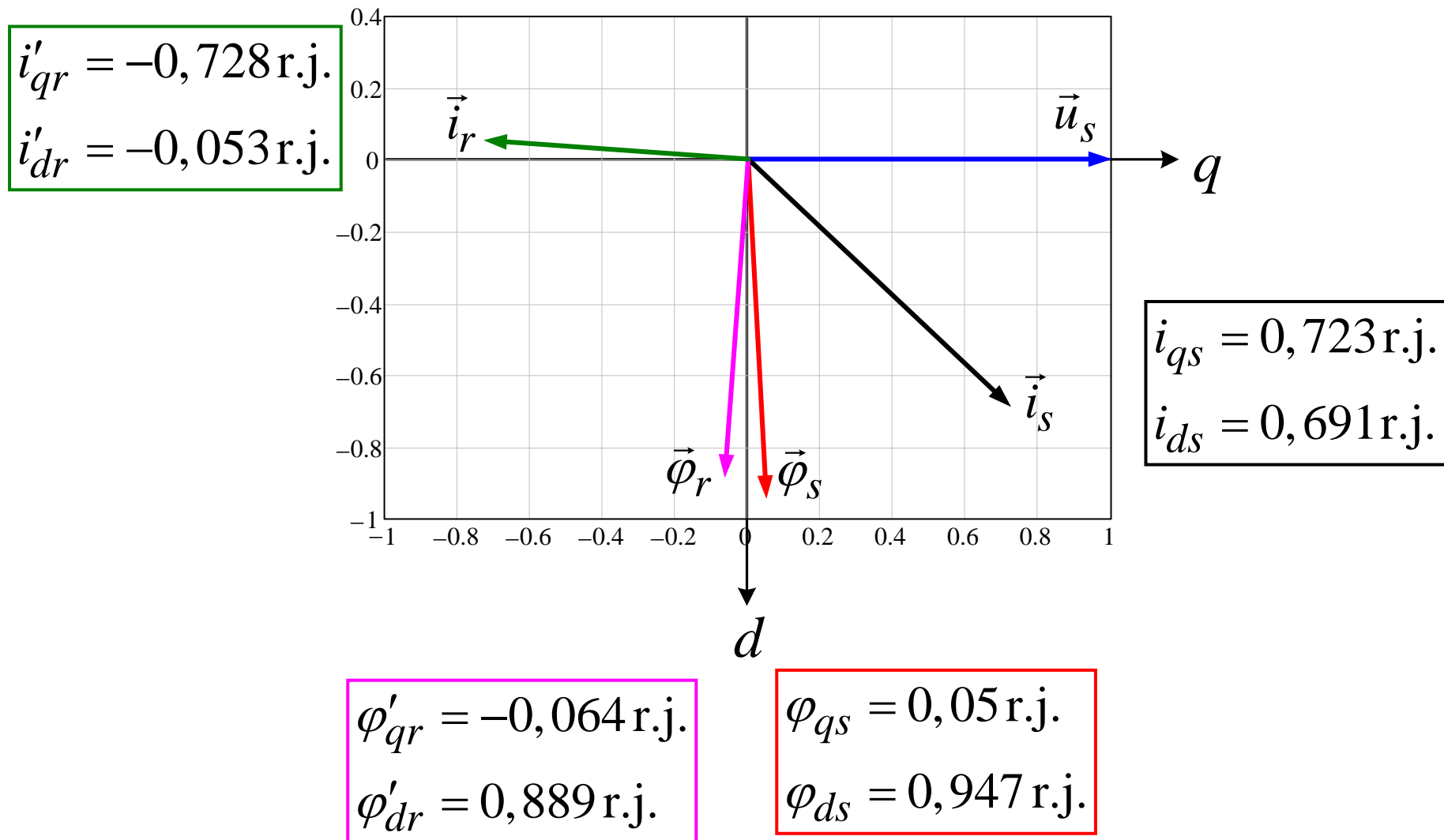
$$\varphi_{ds} = L_s \cdot i_{ds} + M \cdot i'_{dr} \quad (6)$$

$$\mathbf{0} = L'_r \cdot i'_{qr} + M \cdot i_{qs} \quad (7)$$

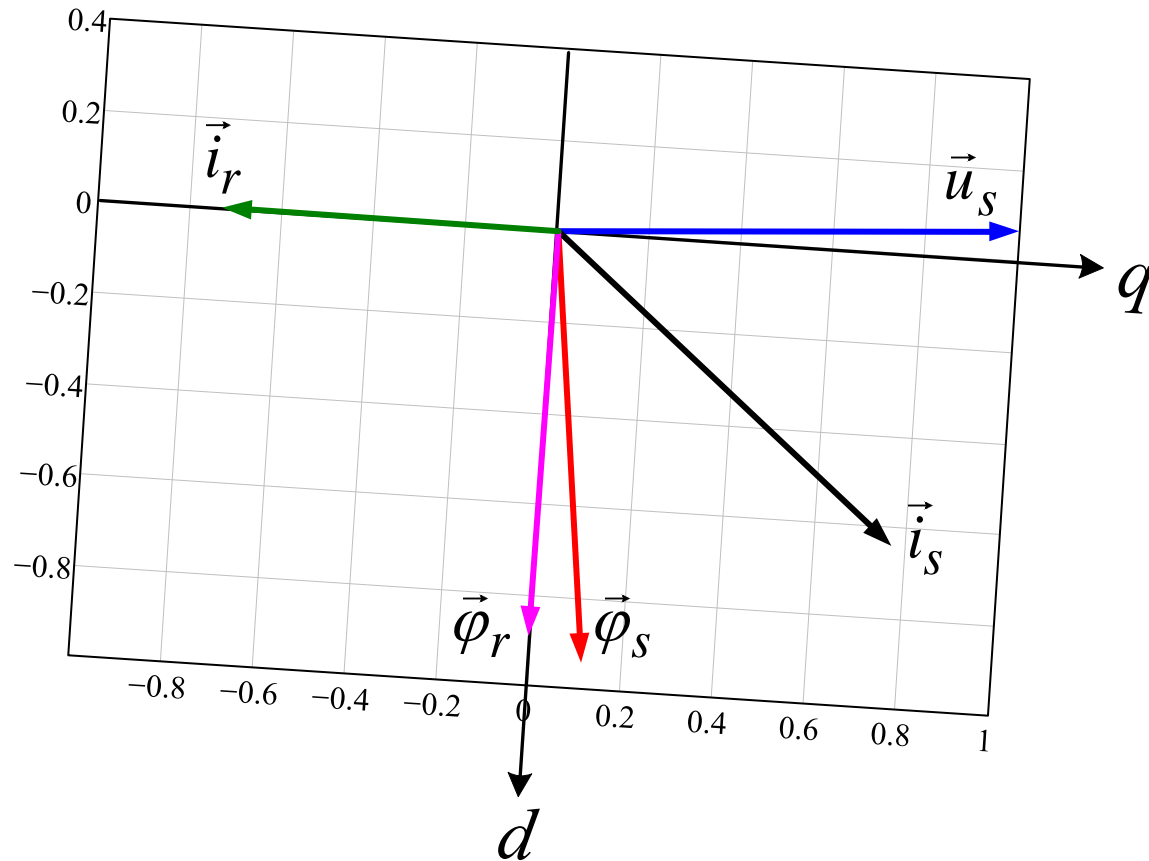
$$\varphi'_{dr} = L'_r \cdot i'_{dr} + M \cdot i_{ds} \quad (8)$$

$$m_e = \frac{3}{2} \cdot P \cdot \frac{M}{L'_r} \cdot (i_{qs} \cdot \varphi'_{dr} - i_{ds} \cdot \mathbf{0}) = \frac{3}{2} \cdot P \cdot \frac{M}{L'_r} \cdot i_{qs} \cdot \varphi'_{dr} \quad (9)$$

Nominalna radna tačka, ustaljeno stanje. Koordinatni sistem orijentisan tako da bude  $u_{ds} = 0, u_{qs} = 1 \text{ r.j.}$



Nominalna radna tačka, ustaljeno stanje. Koordinatni sistem orijentisan tako da bude  $\varphi'_{qr} = 0, \varphi'_{dr} = 0,891 \text{ r.j.}$

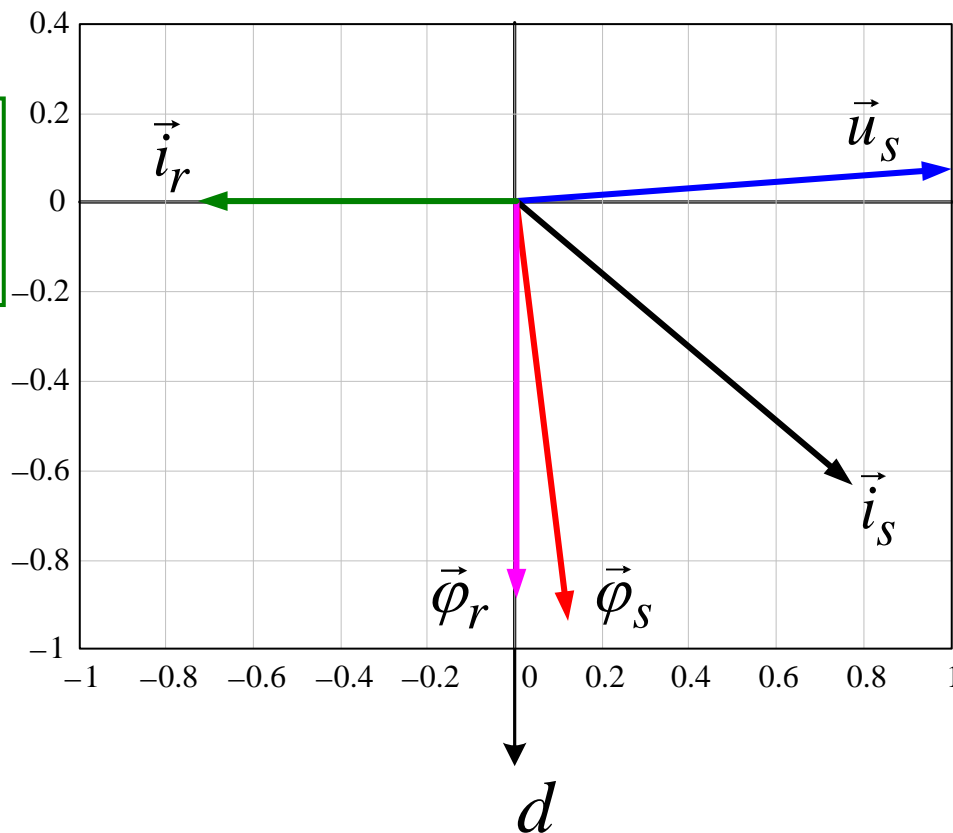


Strelice su ostale na svojim mestima, koordinatni sistem je “zaokrenut”.



Nominalna radna tačka, ustaljeno stanje. Koordinatni sistem orijentisan tako da bude  $\varphi'_{qr} = 0, \varphi'_{dr} = 0,891 \text{ r.j.}$

$$\begin{aligned} i'_{qr} &= -0,73 \text{ r.j.} \\ i'_{dr} &= 0 \end{aligned}$$



$$\begin{aligned} u_{qs} &= 0,997 \text{ r.j.} \\ u_{ds} &= -0,072 \text{ r.j.} \end{aligned}$$

$$\begin{aligned} i_{qs} &= 0,771 \text{ r.j.} \\ i_{ds} &= 0,637 \text{ r.j.} \end{aligned}$$

$$\begin{aligned} \varphi_{qs} &= 0,119 \text{ r.j.} \\ \varphi_{ds} &= 0,941 \text{ r.j.} \end{aligned}$$

$$(3) \quad \omega_r = -\frac{R'_r \cdot i'_{qr}}{\phi'_{dr}}$$

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$$(7) \quad i'_{qr} = -\frac{M \cdot i_{qs}}{L'_r}$$

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$$(8) \quad i'_{dr} = \frac{\phi'_{dr} - M \cdot i_{ds}}{L'_r}$$

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$$(4) \quad p\phi'_{dr} = -R'_r \cdot i'_{dr}$$

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$$(8) \rightarrow (4) \quad p\phi'_{dr} = -R'_r \cdot \frac{\phi'_{dr} - M \cdot i_{ds}}{L'_r}$$

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$$T_r = \frac{L'_r}{R'_r} = \frac{M + \lambda'_r}{R'_r}$$

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$$T_r \cdot p\phi'_{dr} = -\phi'_{dr} + M \cdot i_{ds}$$

$$\phi'_{dr} = \frac{M}{1 + T_r \cdot p} \cdot i_{ds}$$

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(7) → (3)

$$\omega_r = \frac{R'_r}{L'_r} \cdot \frac{M \cdot i_{qs}}{\phi'_{dr}} = \frac{1}{T_r} \cdot \frac{M \cdot i_{qs}}{\phi'_{dr}}$$

# Model pogona sa vektorskim upravljanjem

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$$u_{qs} = R_s \cdot i_{qs} + p\varphi_{qs} + \omega_s \cdot \varphi_{ds}$$

$$u_{ds} = R_s \cdot i_{ds} + p\varphi_{ds} - \omega_s \cdot \varphi_{qs}$$

---

$$\varphi'_{dr} = \frac{M}{1 + T_r \cdot p} \cdot i_{ds}$$

$$\omega_r = \frac{R'_r}{L'_r} \cdot \frac{M \cdot i_{qs}}{\varphi'_{dr}} = \frac{1}{T_r} \cdot \frac{M \cdot i_{qs}}{\varphi'_{dr}}$$

---

$$\varphi_{qs} = \frac{L_s \cdot L'_r - M^2}{L'_r} \cdot i_{qs}$$

$$\varphi_{ds} = \frac{L_s \cdot L'_r - M^2}{L'_r} \cdot i_{ds} + \varphi'_{dr}$$

---

$$m_e = \frac{3}{2} P \frac{M}{L'_r} \cdot i_{qs} \cdot \varphi'_{dr}$$

$$\omega_{rs} = \omega_s = \omega + \omega_r$$

$$\theta_{rs}(t) = \theta_s(t) = \theta(t) + \theta_r(t) = \int_0^t \omega dt + \int_0^t \omega_r dt = \int_0^t \omega_s dt$$

# Model pogona sa vektorskim upravljanjem u ustaljenom stanju

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$$u_{qs} = R_s \cdot i_{qs} + \omega_s \cdot \varphi_{ds}$$

$$u_{ds} = R_s \cdot i_{ds} - \omega_s \cdot \varphi_{qs}$$

---

$$\varphi'_{dr} = M \cdot i_{ds} \quad \omega_r = \frac{1}{T_r} \cdot \frac{i_{qs}}{i_{ds}} \quad T_r = \frac{L'_r}{R'_r} = \frac{M + \lambda'_r}{R'_r}$$

$$\varphi_{qs} = \frac{L_s \cdot L'_r - M^2}{L'_r} \cdot i_{qs} \quad \varphi_{ds} = L_s \cdot i_{ds} \quad L_s = M + \lambda_s$$

---

$$m_e = \left( \frac{3}{2} \cdot P \right) \cdot \frac{M^2}{L'_r} \cdot i_{qs} \cdot i_{ds}$$

$$\omega_s = \omega + \omega_r = (P \cdot \omega_m) + \omega_r$$

# Vektorski upravljani asinhroni motor

$i_{ds}$  Određuje fluks.

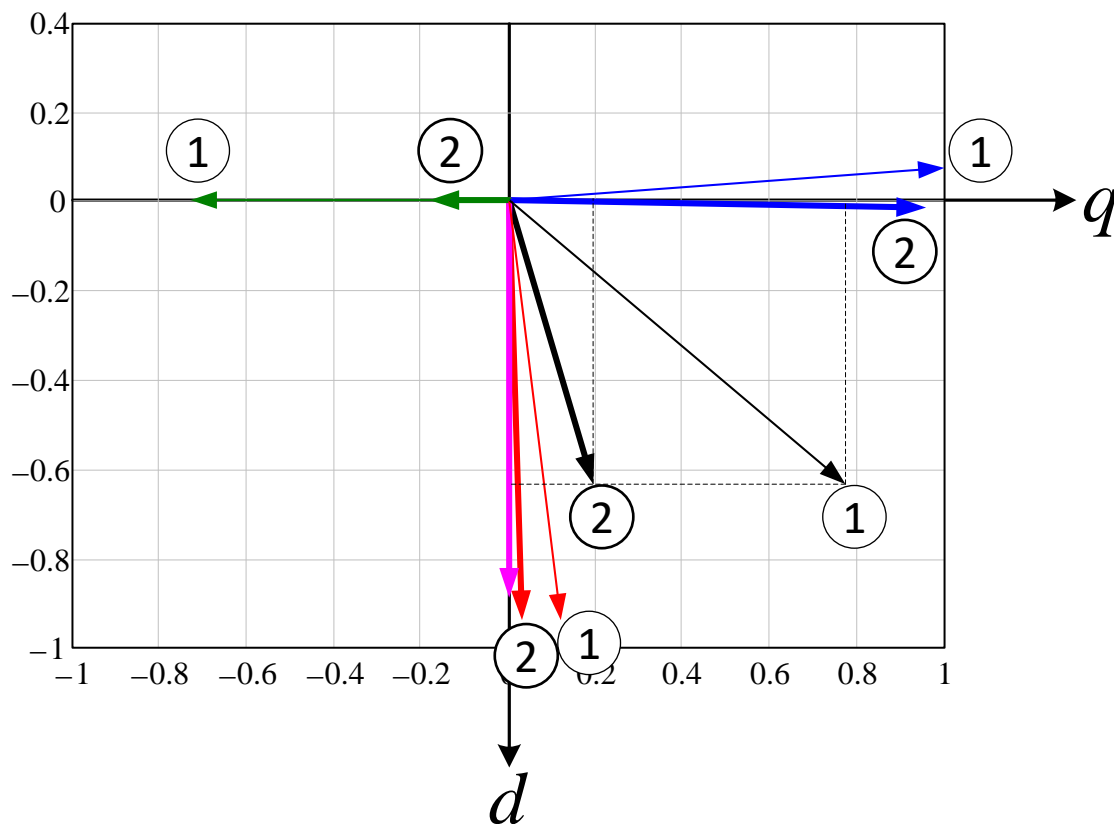
$i_{qs}$  Određuje moment.

- Uspostavljanje fluksa u motoru ostvaruje se uspostavljanjem struje u statorskim namotajima ( $i_{ds}$ ).
- Komanda momenta ( $i_{qs}$ ) se ne dozvoljava u toku procesa pobuđivanja.

# Promena opterećenja kod vektorski regulisanog asinhronog motora ( $\omega_s = const.$ )

Rasterećenje:  $\textcircled{1} \rightarrow \textcircled{2}$

Opterećenje:  $\textcircled{2} \rightarrow \textcircled{1}$



$$i_{qs1} = 0,771 \text{ r.j.}, \quad i_{ds1} = 0,637 \text{ r.j.}$$

$$i_{qs2} = 0,193 \text{ r.j.}, \quad i_{ds2} = 0,637 \text{ r.j.}$$

$$\varphi'_{qr1} = 0, \quad \varphi'_{dr1} = 0,891 \text{ r.j.}$$

$$\varphi'_{qr2} = 0, \quad \varphi'_{dr2} = 0,891 \text{ r.j.}$$

$$\varphi_{qs1} = 0,119 \text{ r.j.}, \quad \varphi_{ds1} = 0,941 \text{ r.j.}$$

$$\varphi_{qs2} = 0,03 \text{ r.j.}, \quad \varphi_{ds2} = 0,941 \text{ r.j.}$$

$$u_{qs1} = 0,997 \text{ r.j.}, \quad u_{ds1} = -0,072 \text{ r.j.}$$

$$u_{qs2} = 0,995 \text{ r.j.}, \quad u_{ds2} = 0,017 \text{ r.j.}$$

$$i'_{qr1} = -0,730 \text{ r.j.}, \quad i'_{dr1} = 0 \text{ r.j.}$$

$$i'_{qr2} = -0,182 \text{ r.j.}, \quad i'_{dr2} = 0 \text{ r.j.}$$

# Načini realizacije vektorskog upravljanja

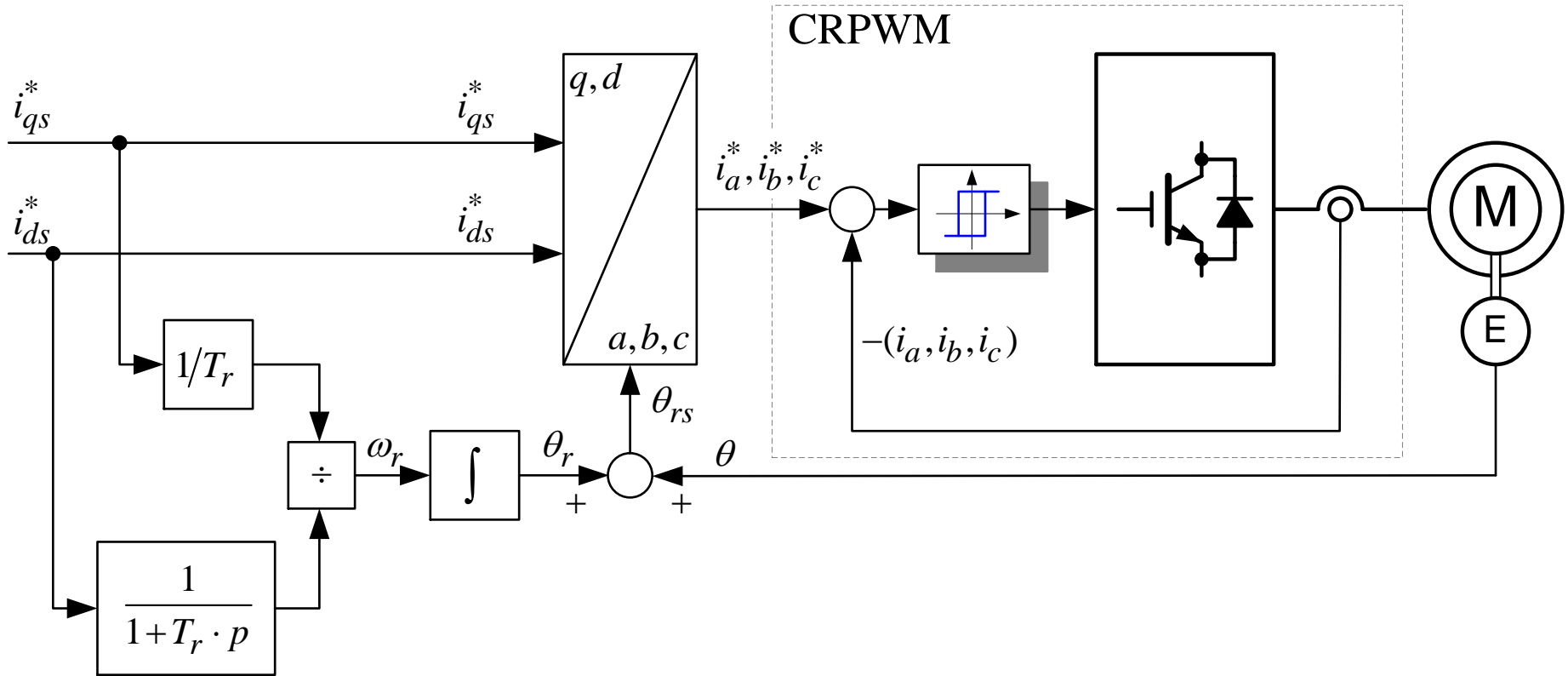
## Indirektno vektorsko upravljanje

- Na osnovu zadatih struja izračunava se rotorska učestanost ( $\omega_r$ )
- Zbir rotorske učestanosti i brzine se koristi kao brzina referentnog sistema, a ugao sistema se dobija integracijom brzine referentnog sistema.
- Varijanta sa integracijom učestanosti rotorskih struja je bolje prilagođena realizacijama sa enkoderom.

## Direktno vektorsko upravljanje

- Ugao referentnog sistema se određuje iz proračuna flukseva (na bazi merenja struja, podataka o naponu i brzini).
- Može se realizovati i bez podatka o uglu (brzini) vratila motora.

# Indirektno vektorsko upravljanje sa strujno regulisanim IŠM inverterom



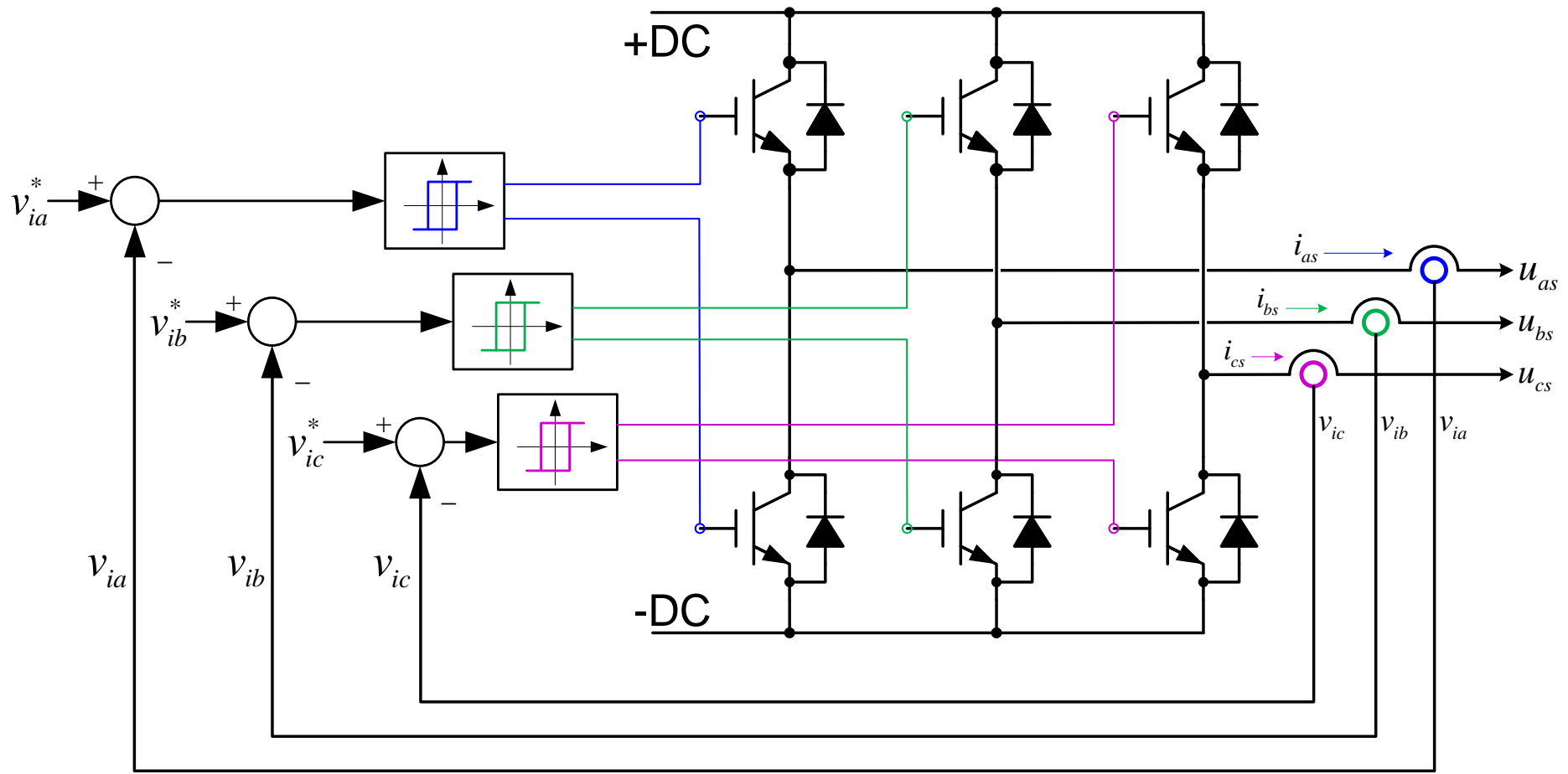
E – Enkoder, davač pozicije vratila motora

CRPWM

Current Regulated Pulse Width Modulated inverter



# Principijelna blok šema strujno regulisanog IŠM invertora

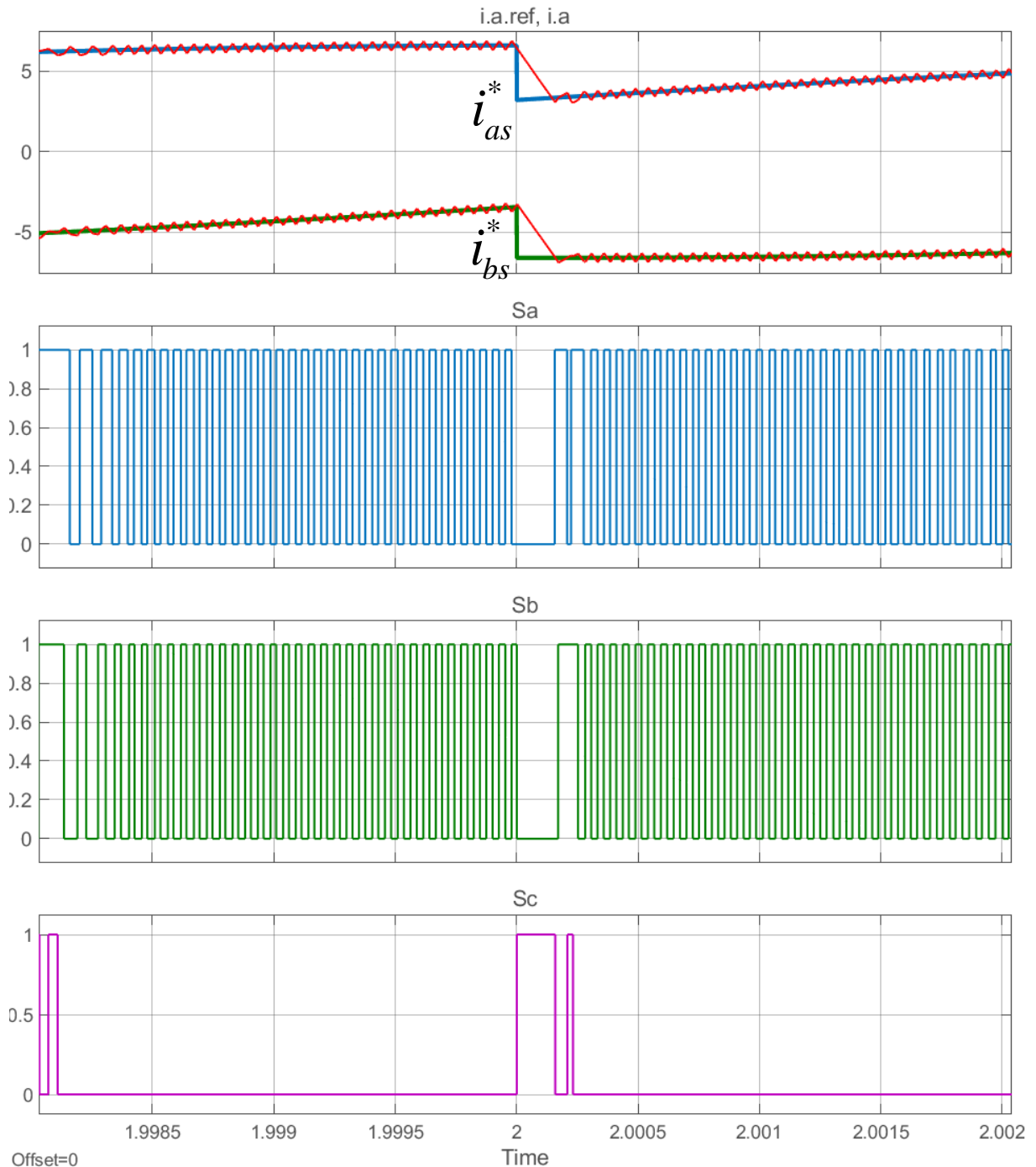


# Prikaz rada histerezisnog regulatora struje

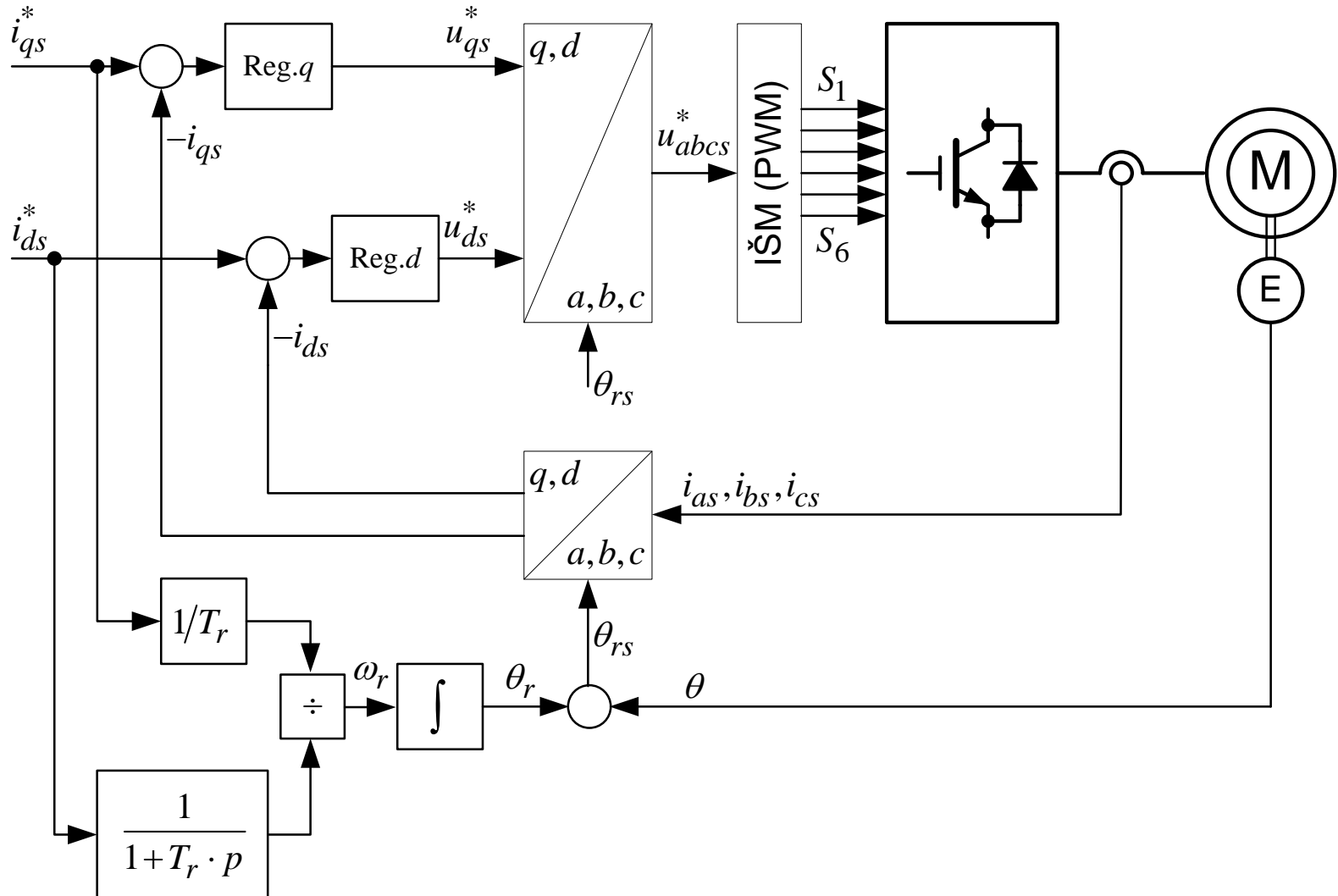
**Sa**  
Stanje gornjeg prekidača u fazi a

**Sb**  
Stanje gornjeg prekidača u fazi b

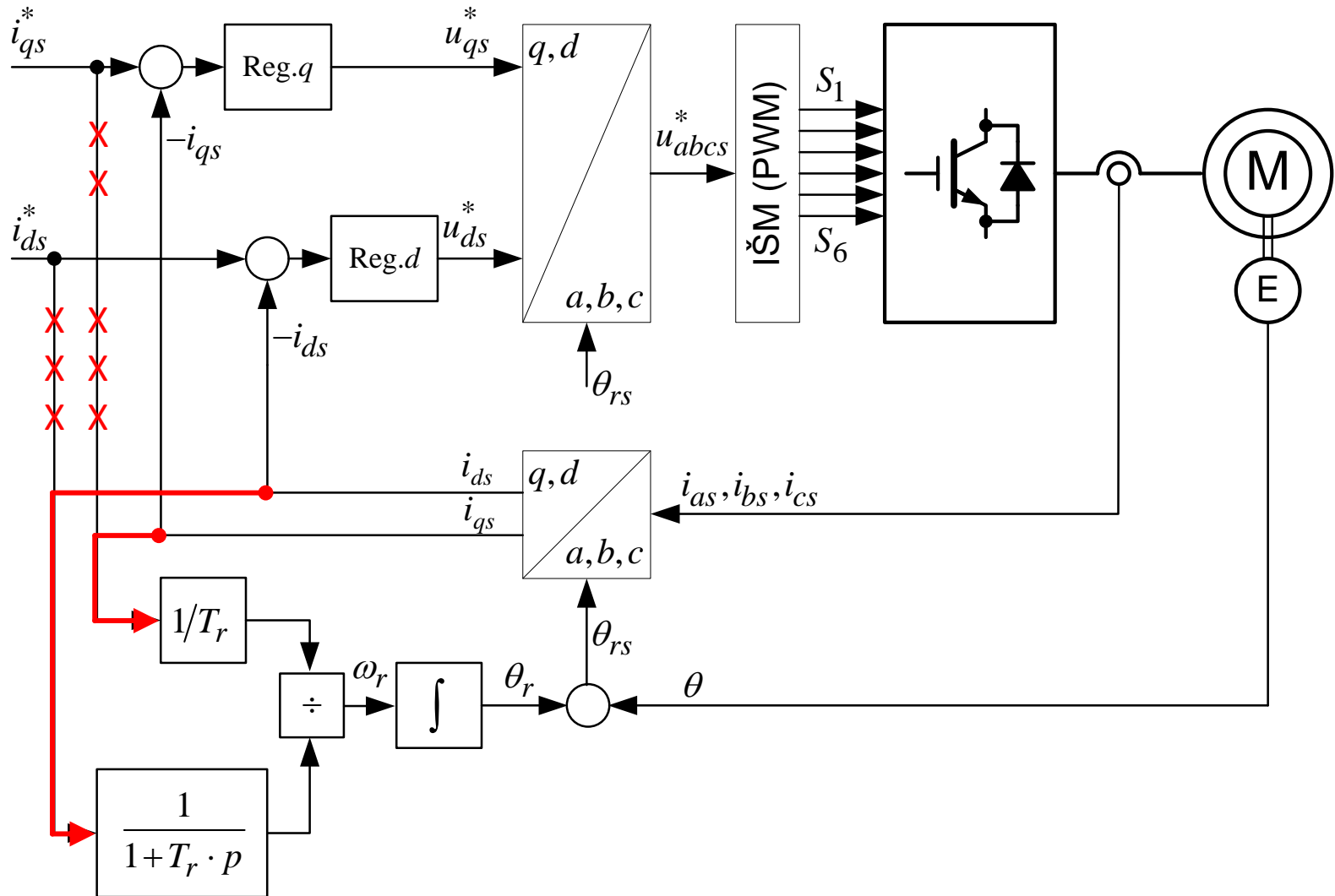
**Sc**  
Stanje gornjeg prekidača u fazi c



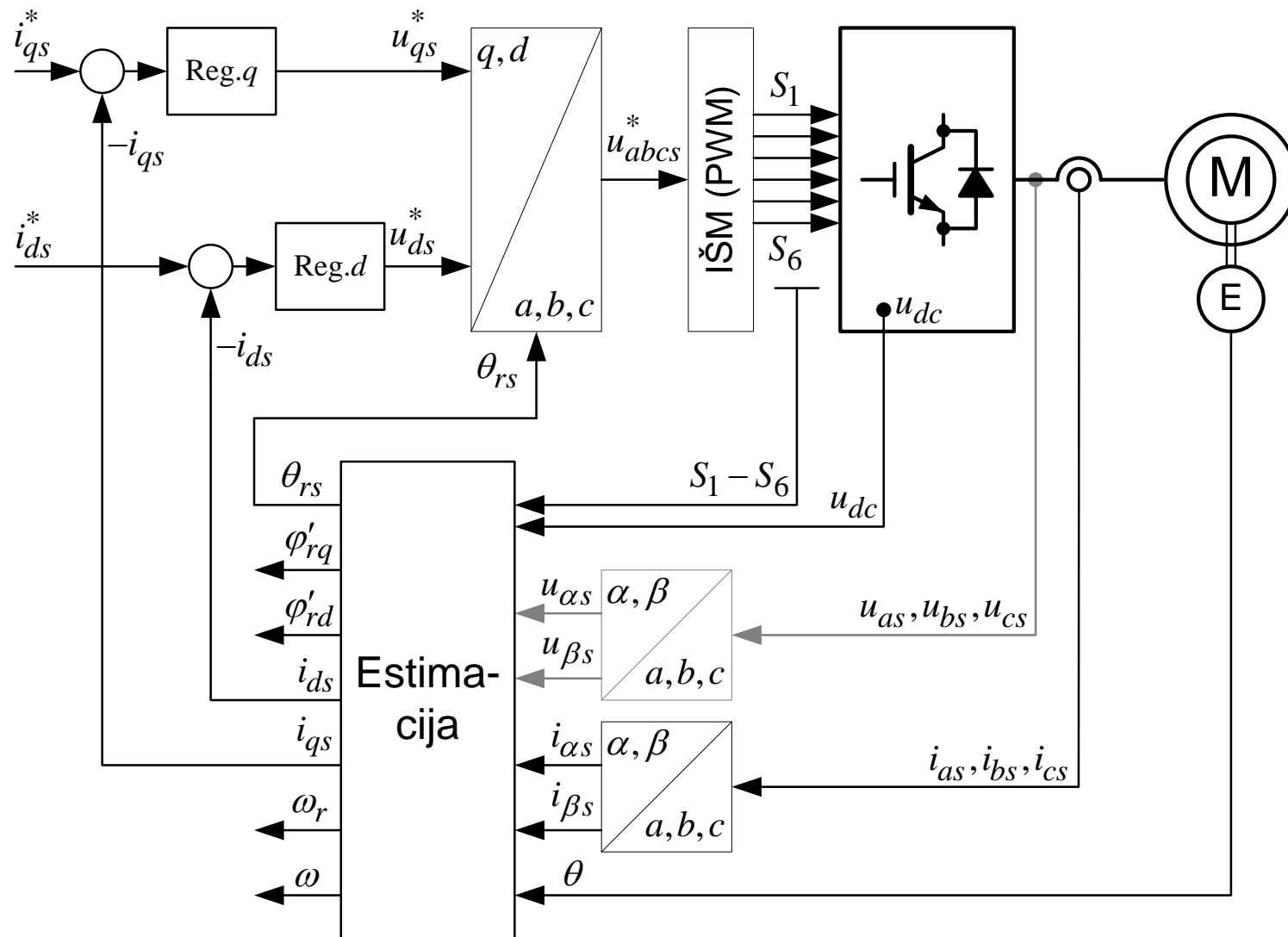
# Indirektno vektorsko upravljanje sa IŠM invertorom i regulacijom struje u sinhrono rotirajućem koordinatnom sistemu



# ~~Indirektno~~ **Direktno** vektorsko upravljanje sa IŠM invertorom i regulacijom struje u sinhrono rotirajućem koordinatnom sistemu



# Direktno vektorsko upravljanje sa IŠM inverterom i regulacijom struje u sinhrono rotirajućem koordinatnom sistemu



# Struktura bloka estimacije u direktnom vektorskom upravljanju (naponski estimator flukseva)

$$\varphi_{\alpha s} = \int_0^t (u_{\alpha s} - R_s \cdot i_{\alpha s}) dt$$

$$\varphi'_{\alpha r} = \frac{L_r}{M} \cdot \varphi_{\alpha s} - \frac{L_r \cdot L_r - M^2}{M} \cdot i_{\alpha s}$$

$$\varphi_{\beta s} = \int_0^t (u_{\beta s} - R_s \cdot i_{\beta s}) dt$$

$$\varphi'_{\beta r} = \frac{L_r}{M} \cdot \varphi_{\beta s} - \frac{L_r \cdot L_r - M^2}{M} \cdot i_{\beta s}$$

$$\cos \theta_{rs} = \frac{\varphi'_{\alpha r}}{\sqrt{(\varphi'_{\alpha r})^2 + (\varphi'_{\beta r})^2}}$$

$$\sin \theta_{rs} = -\frac{\varphi'_{\beta r}}{\sqrt{(\varphi'_{\alpha r})^2 + (\varphi'_{\beta r})^2}}$$

# Struktura bloka estimacije u direktnom vektorskom upravljanju (strujni estimator flukseva)

$$\varphi'_{\alpha r} = \int_0^t \left( \frac{R_r}{L_r} \cdot (M \cdot i_{\alpha s} - \varphi'_{\alpha r}) + \varphi_{\beta r} \cdot \omega \right) dt$$

$$\varphi'_{\beta r} = \int_0^t \left( \frac{R_r}{L_r} \cdot (M \cdot i_{\beta s} - \varphi'_{\beta r}) - \varphi_{\alpha r} \cdot \omega \right) dt$$

$$\cos \theta_{rs} = \frac{\varphi'_{\alpha r}}{\sqrt{(\varphi'_{\alpha r})^2 + (\varphi'_{\beta r})^2}}$$

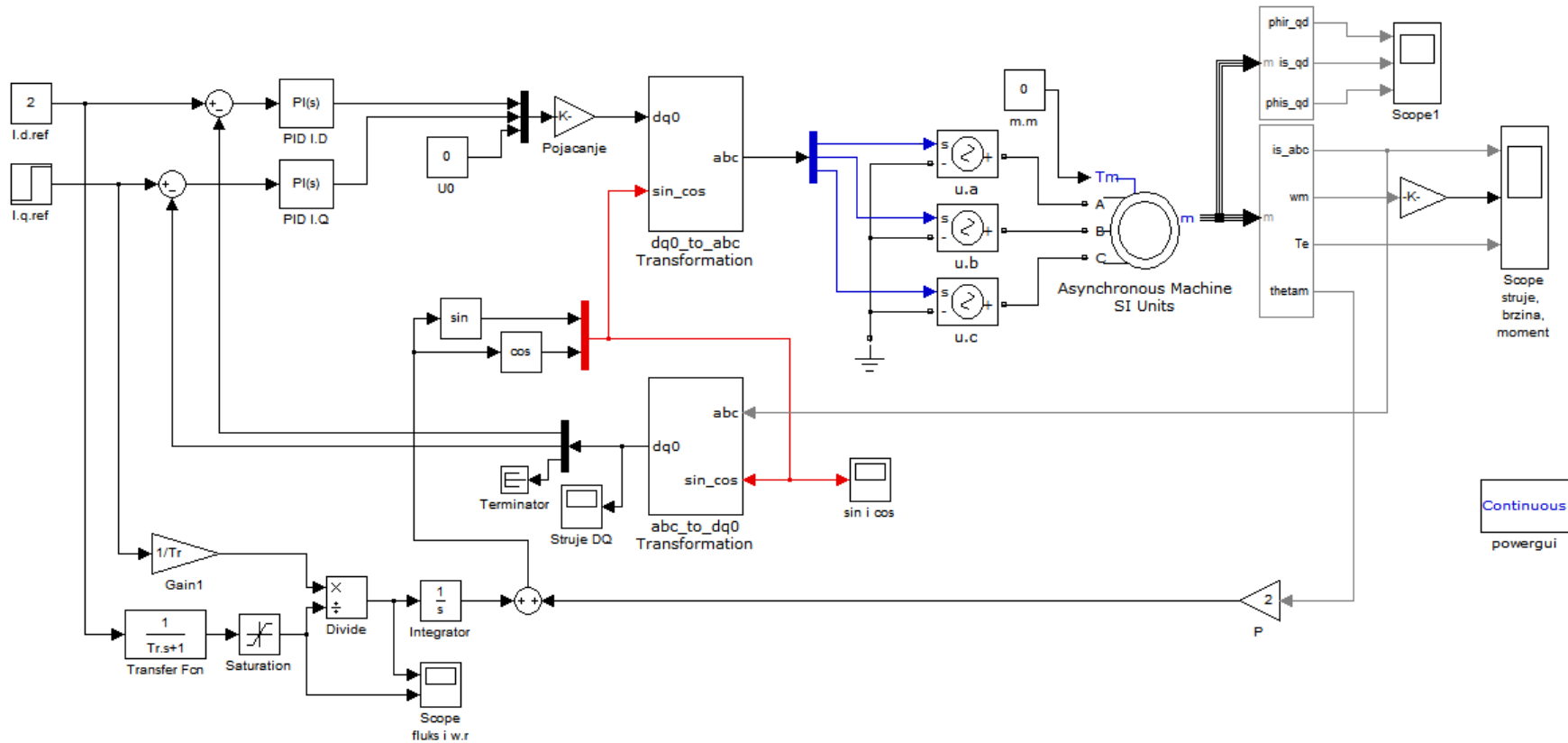
$$\sin \theta_{rs} = -\frac{\varphi'_{\beta r}}{\sqrt{(\varphi'_{\alpha r})^2 + (\varphi'_{\beta r})^2}}$$

# Prikaz rada pogona sa asinhronim motorom sa indirektnim vektorskim upravljanjem

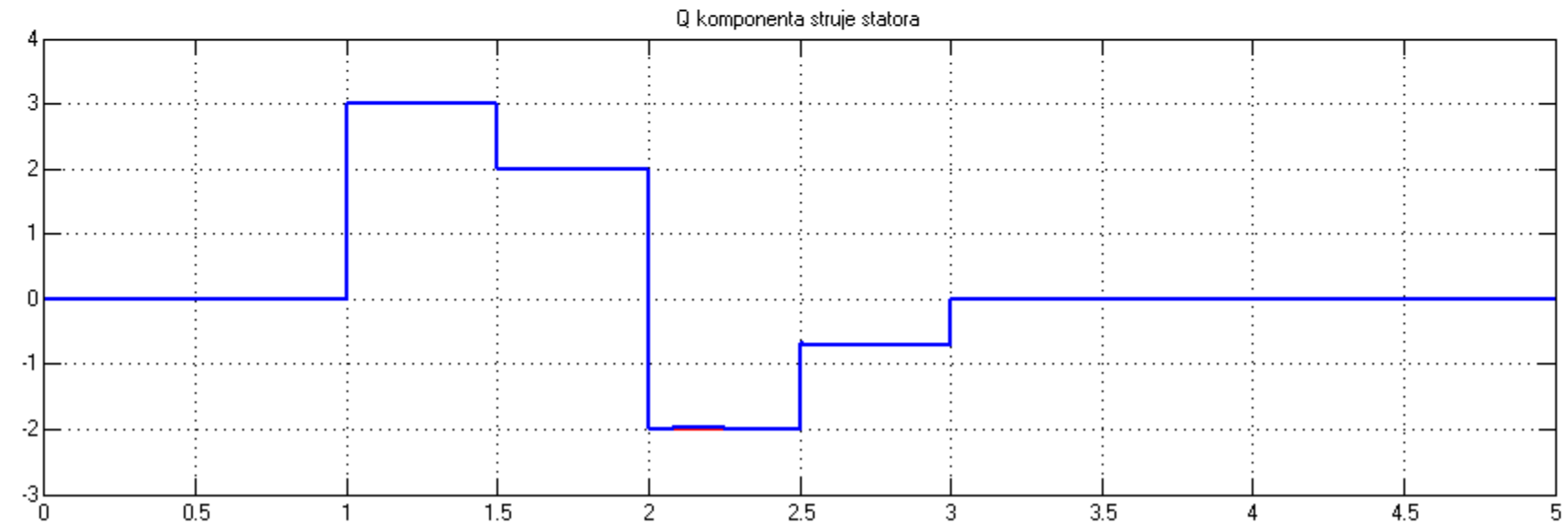
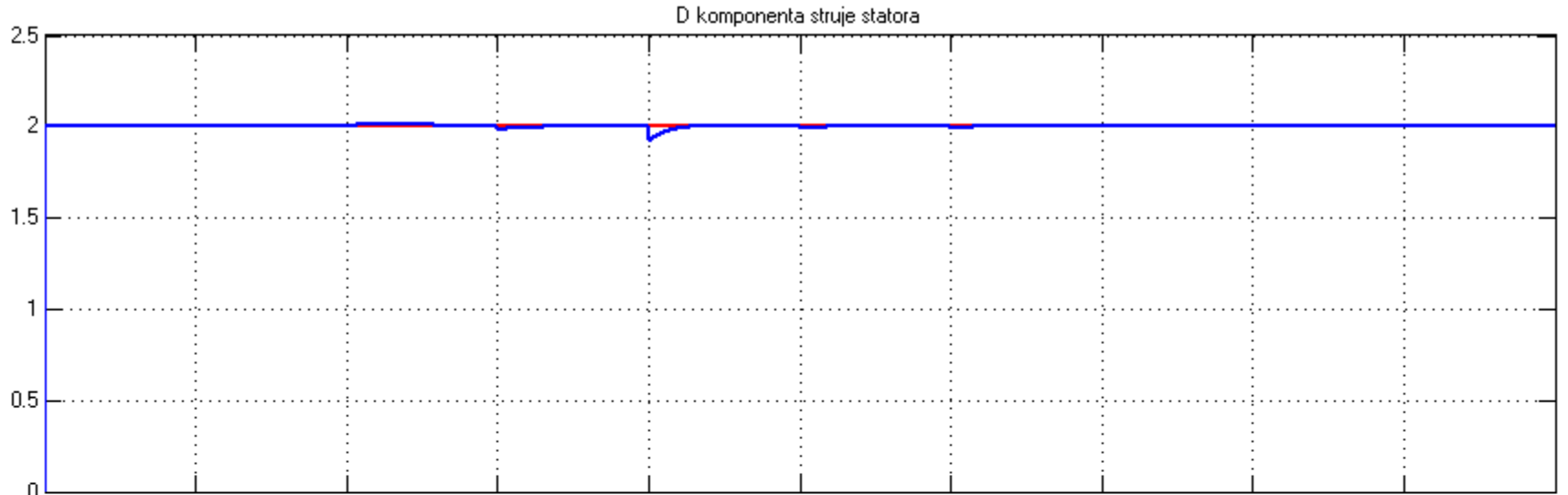
- Regulatori struje su u sinhronom referentnom sistemu, PI tipa, u kontinualnom domenu
- Korišćeni su idealni naponski izvori za napajanje motora
- d- komponenta struje je konstantna
- q- komponenta struje se skokovito menja u vremenu
- Rezultati su dobijeni simulacijom



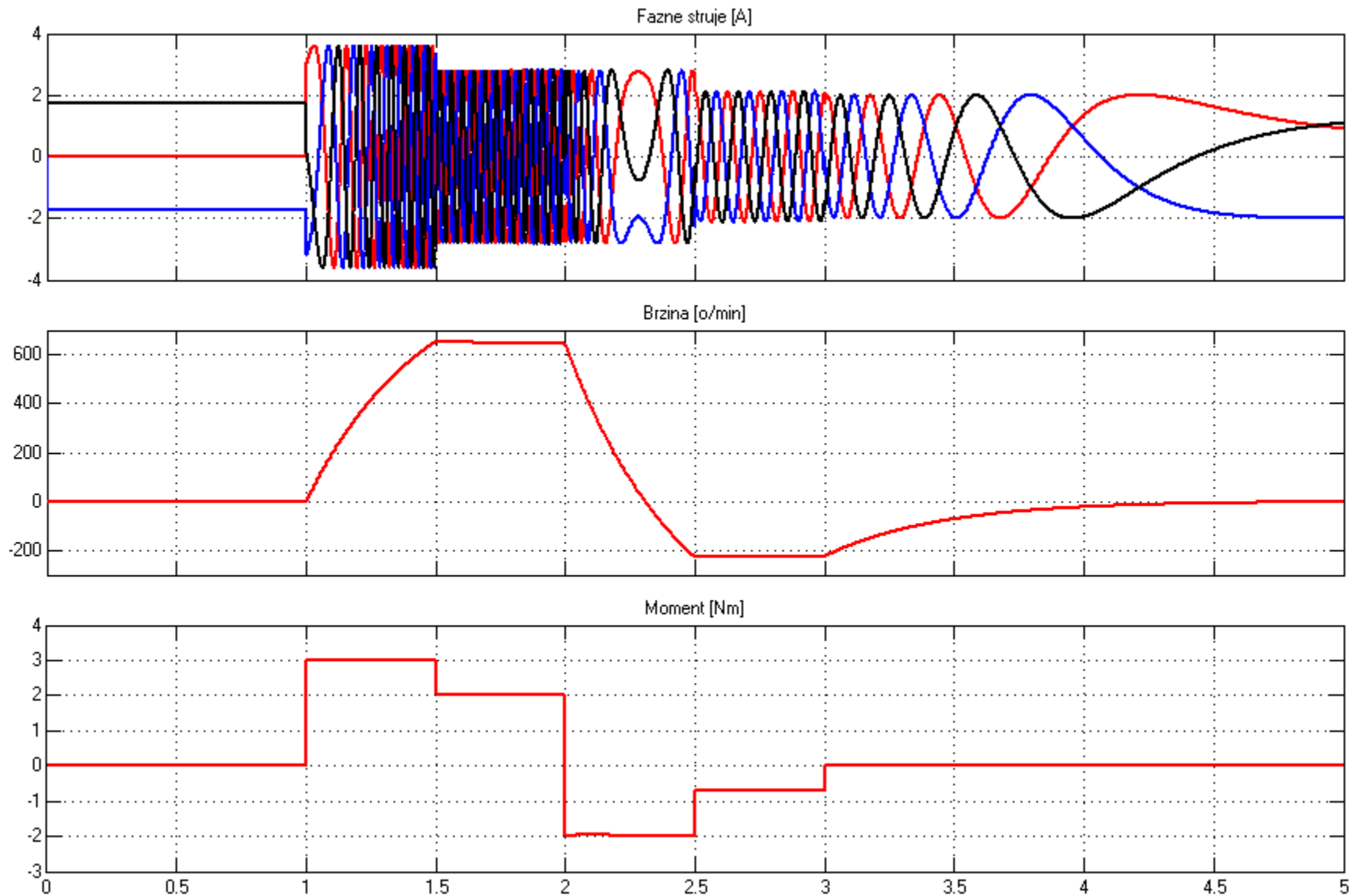
# Simulacioni blok dijagram



# d- i q- komponente struje statora (-zadata i -ostvarena)

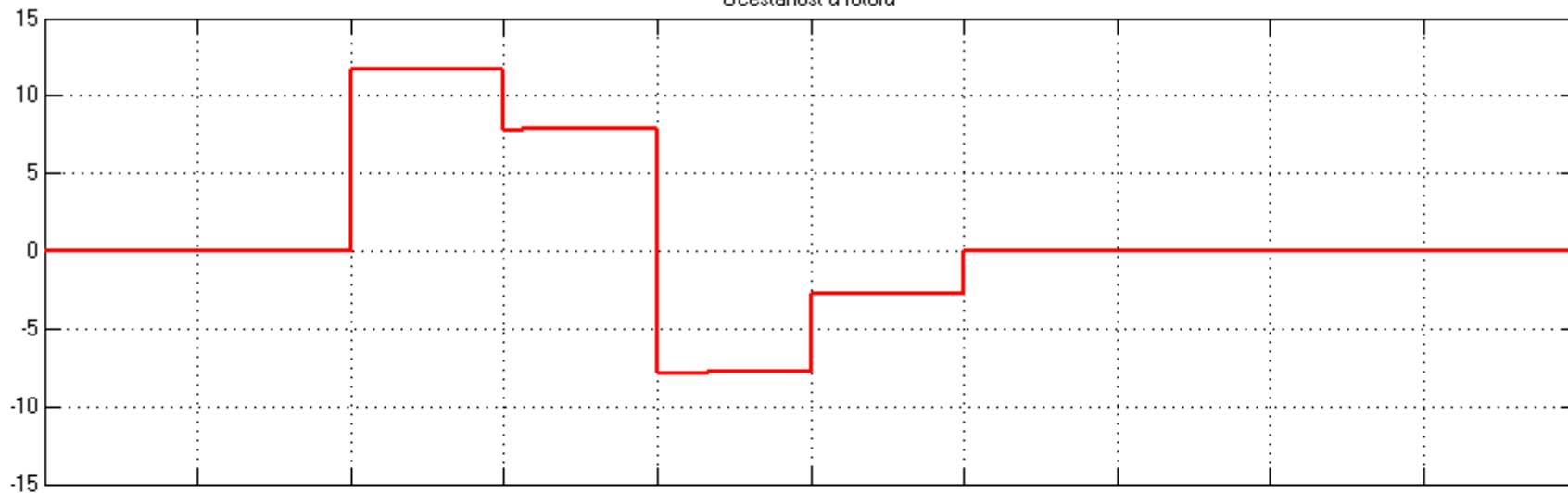


# Fazne struje, brzina i moment motora

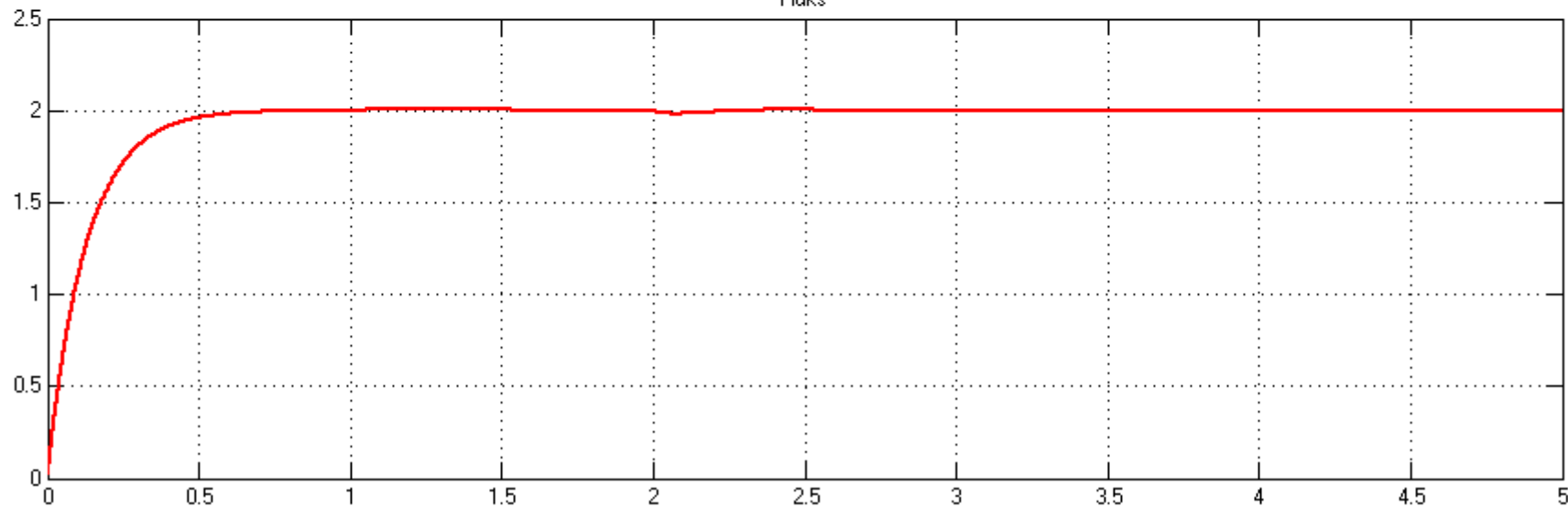


# Učestanost u rotoru, fluks rotora (iz upravljačkog sistema)

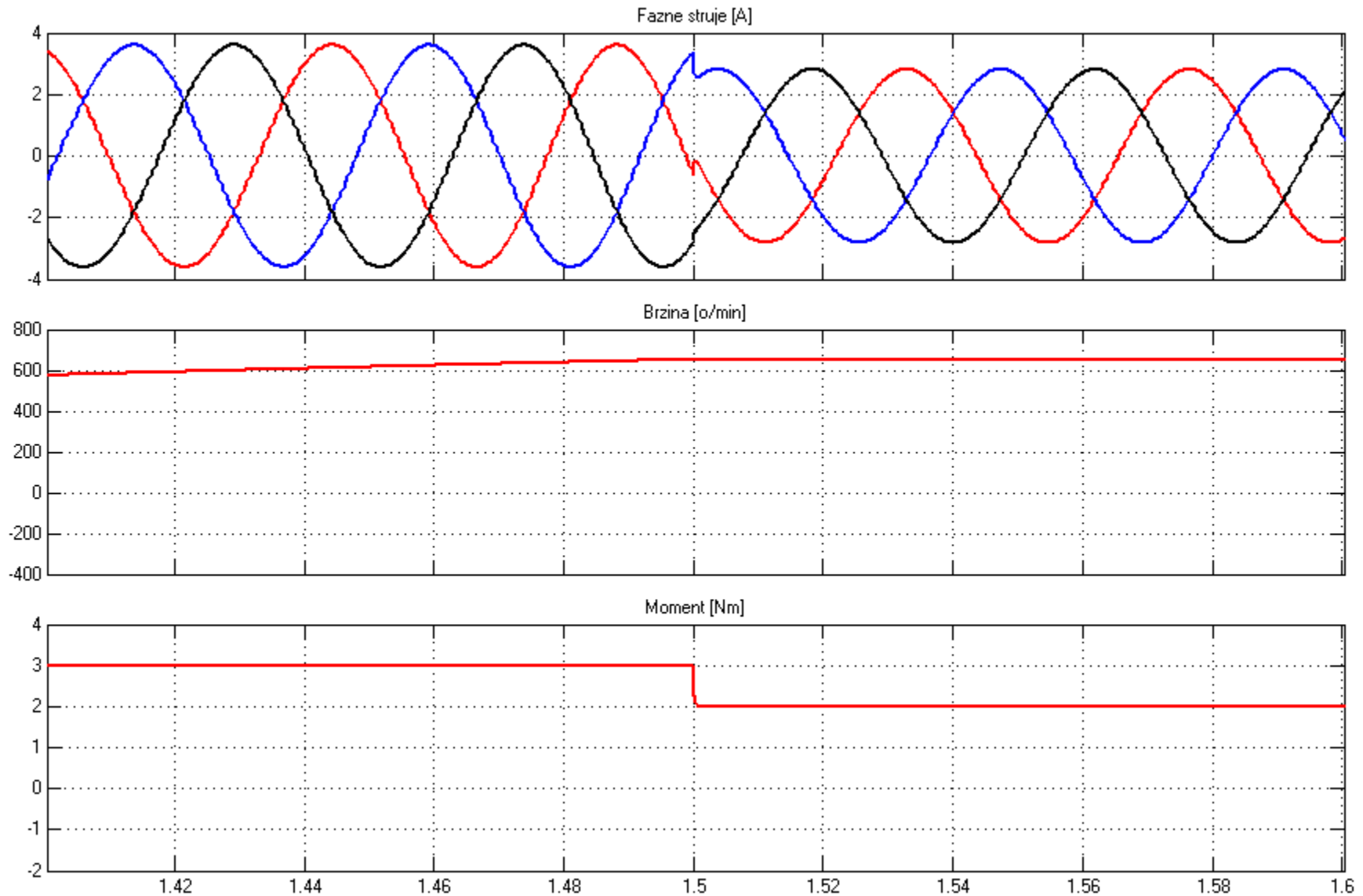
Učestanost u rotoru



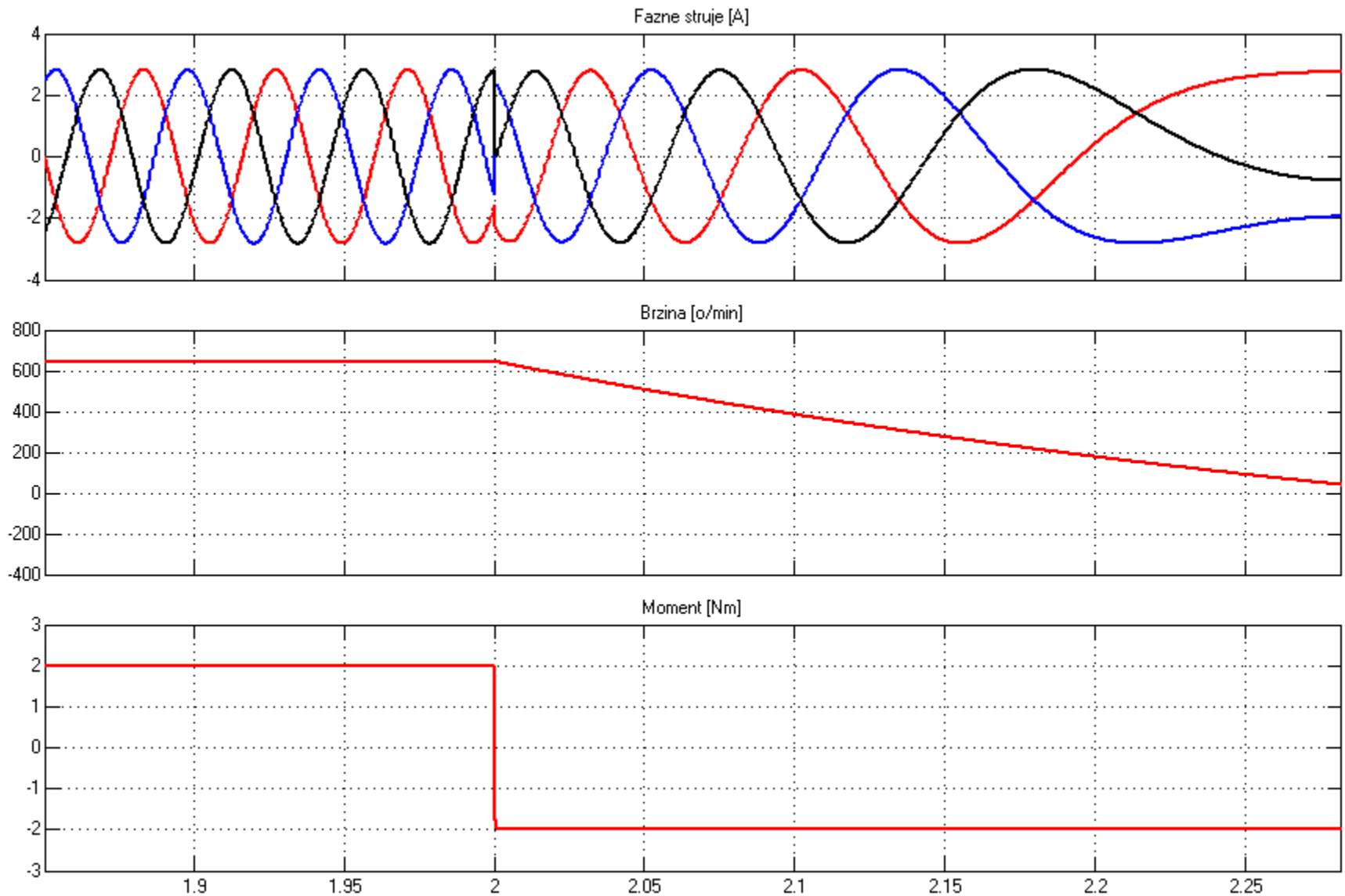
Fluks



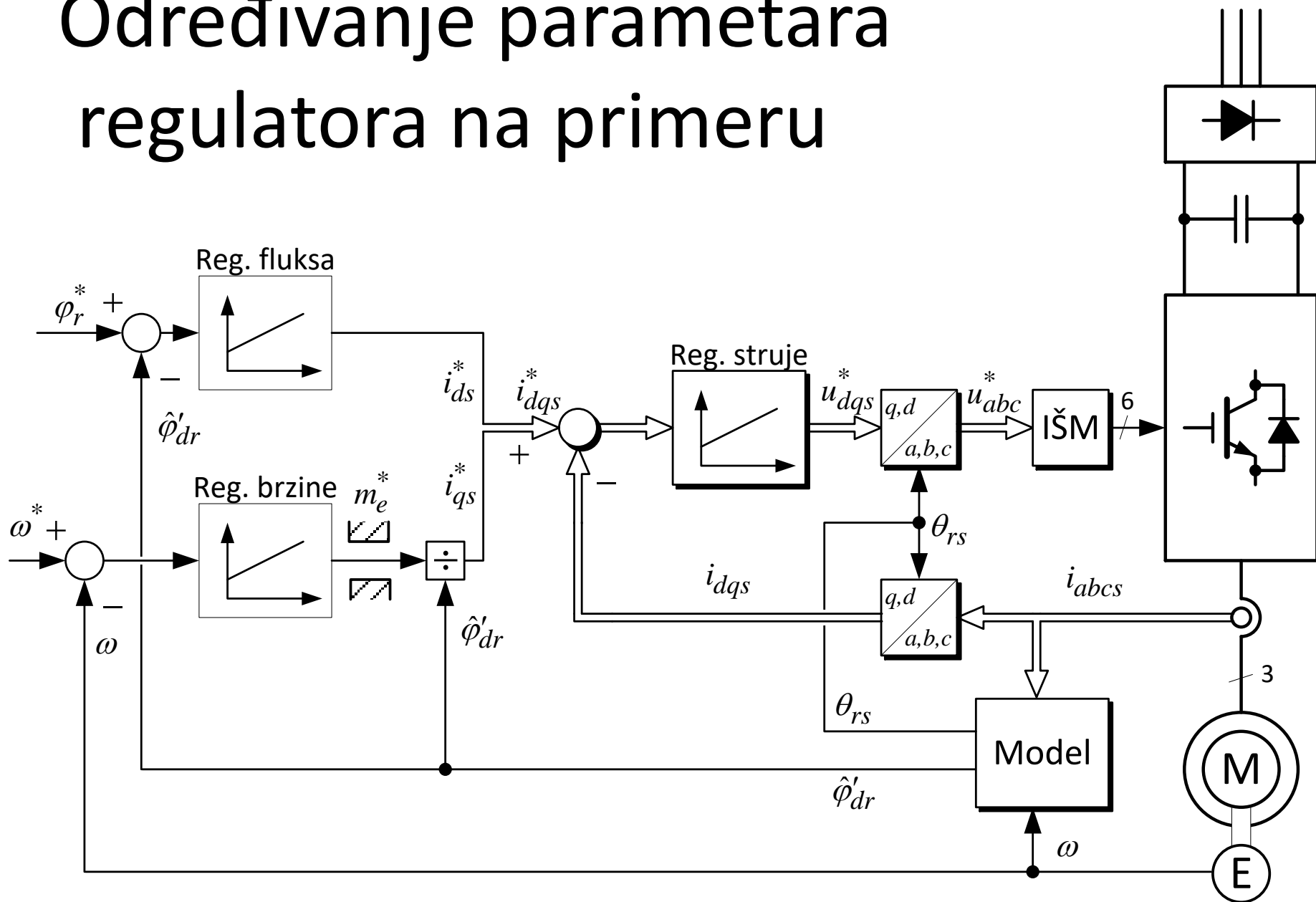
# Fazne struje, brzina i moment motora (uveličan detalj promene q- komponente struje)



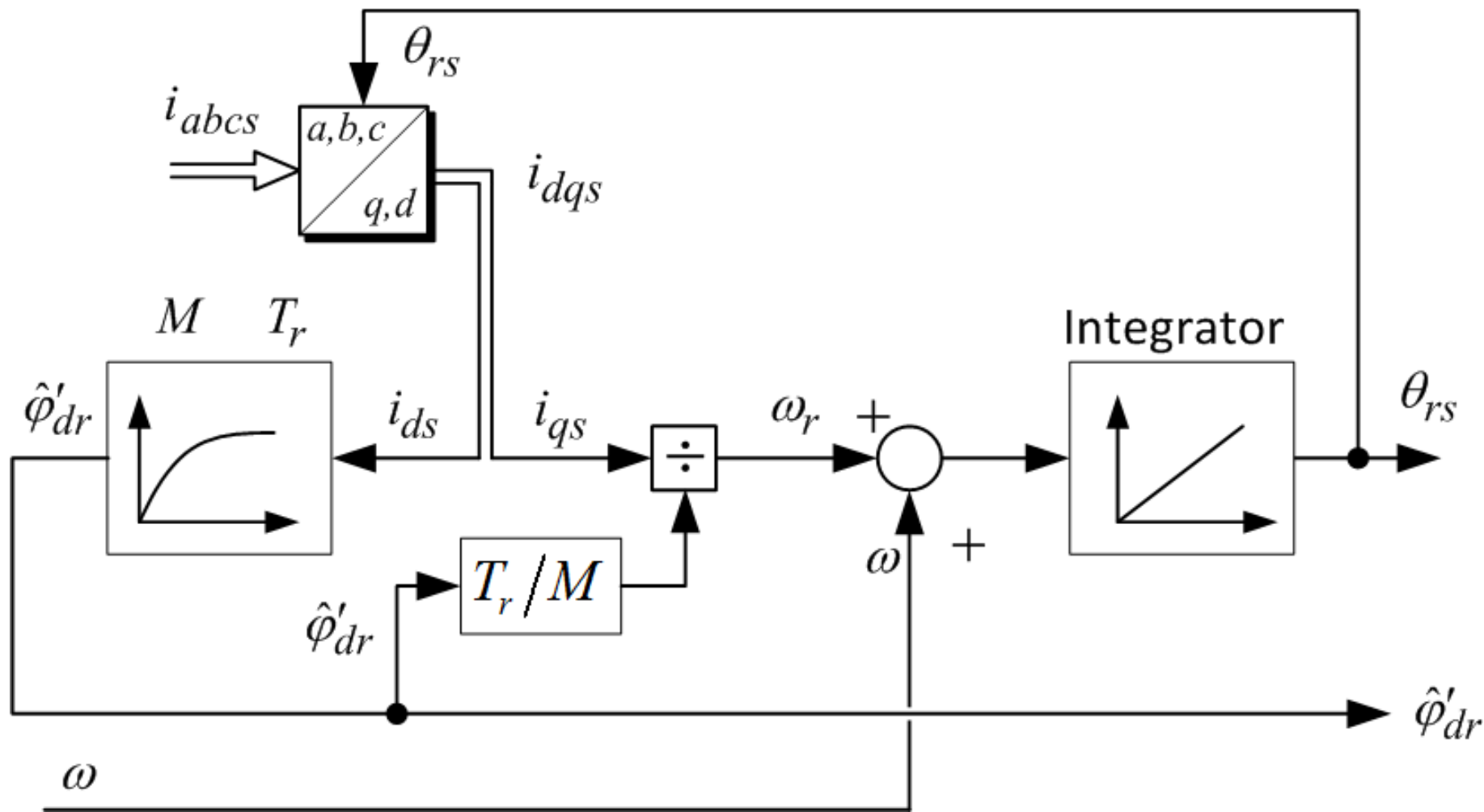
# Fazne struje, brzina i moment motora (uveličan detalj promene q- komponente struje)



# Određivanje parametara regulatora na primeru

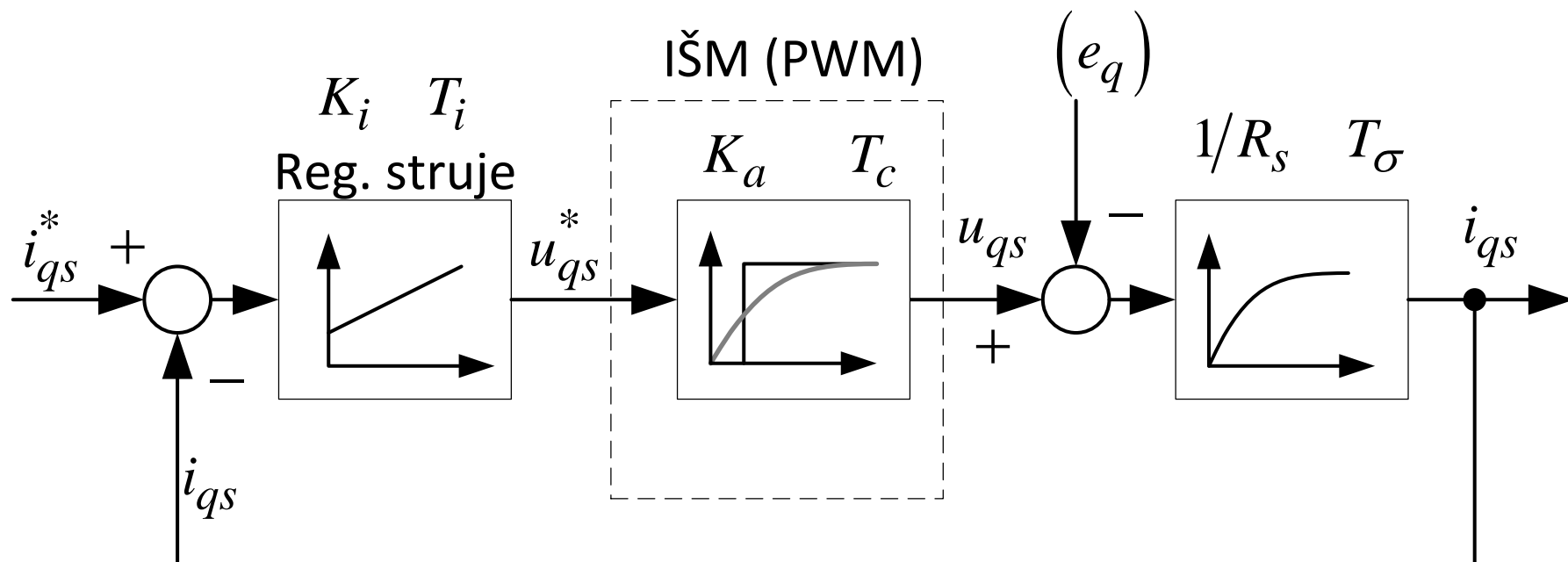


# Model za izračunavanje (estimaciju) ugla $\theta_{rs}$ i rotorskog fluksa $\hat{\varphi}'_{dr}$





# Regulacija struje ( $q$ -osa)

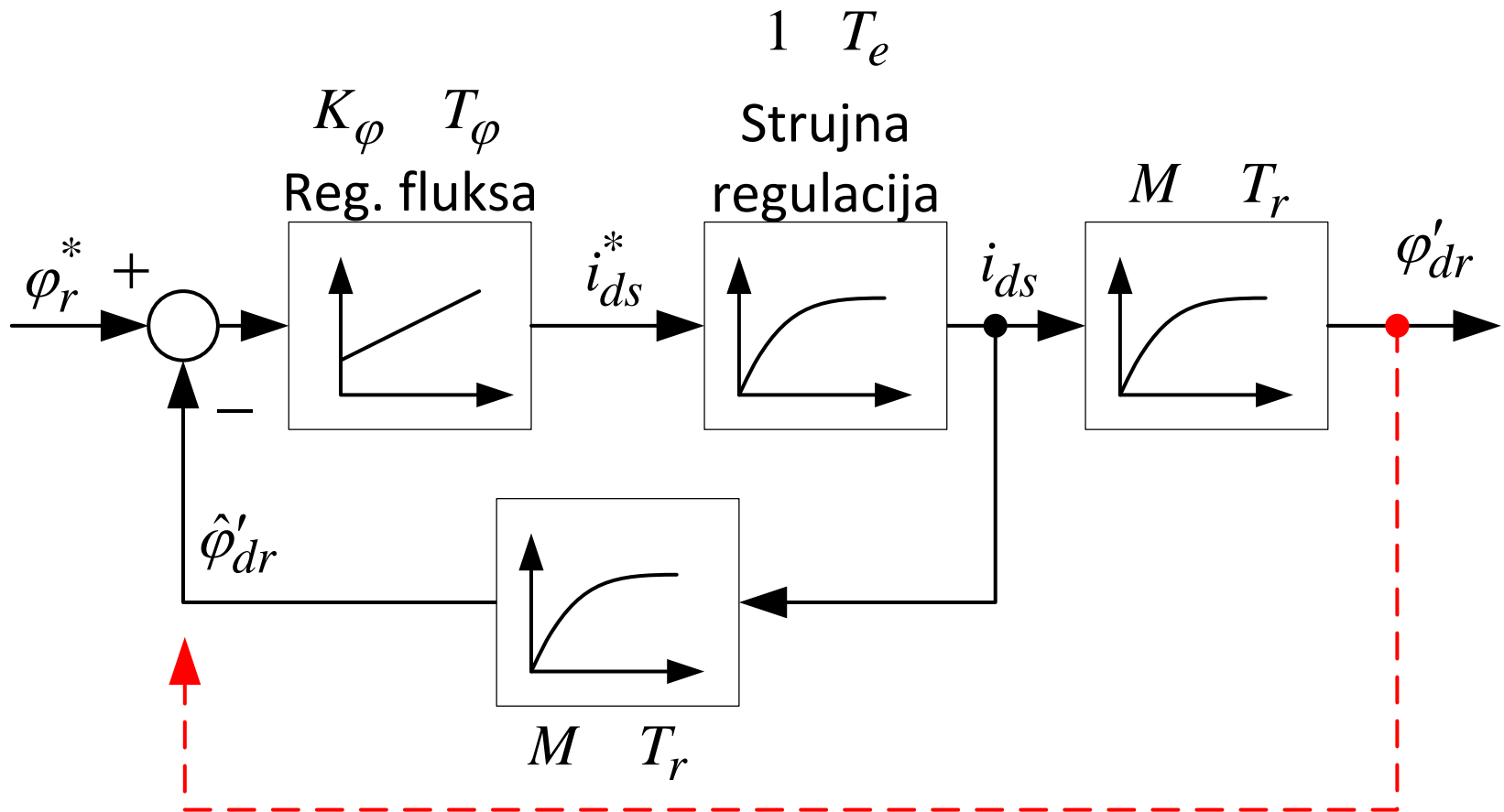


Može se primeniti kompenzacija vremenske konstante i modulni optimum.

$$T_\sigma = \frac{(L_s \cdot L_r' - M^2)}{R_s} / L_r'$$

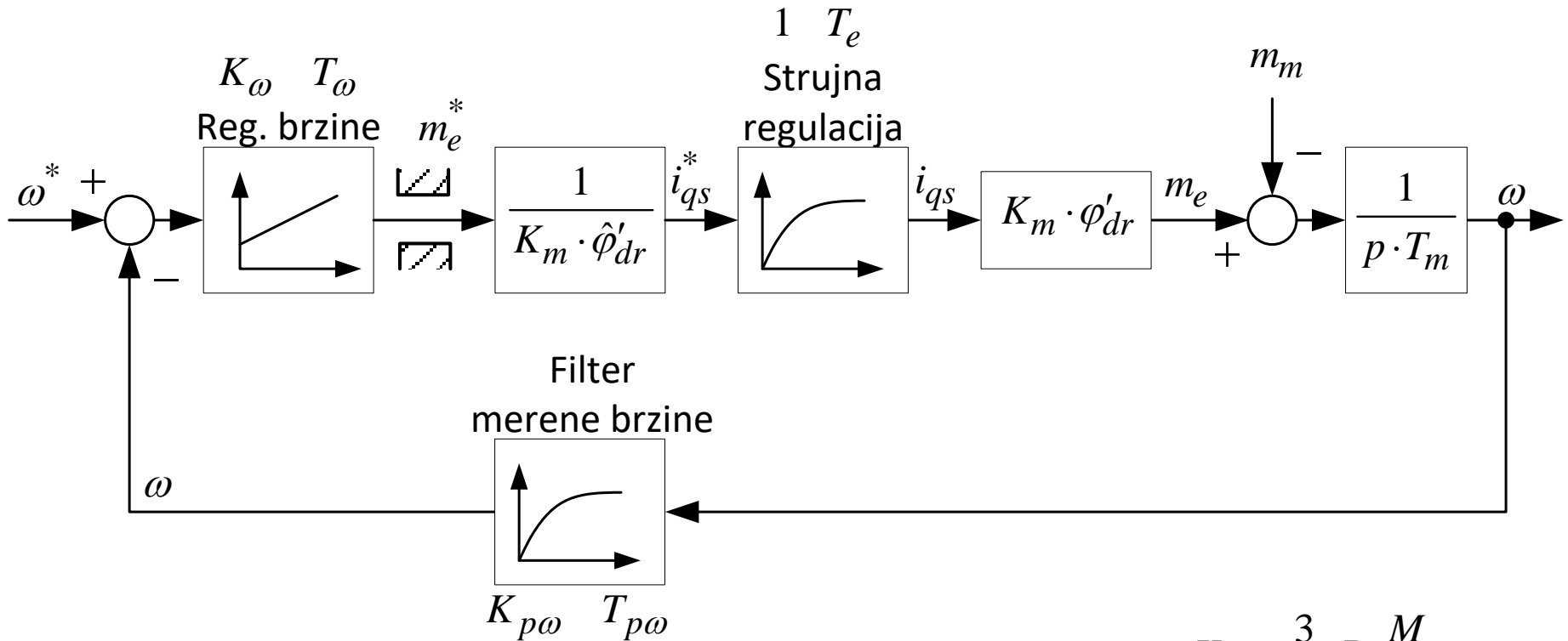
Strujni regulatori u  $q$  i  $d$  osi su simetrični, može se koristiti ista struktura i parametri regulatora.

# Regulacija fluksa



Može se primeniti kompenzacija vremenske konstante i modulni optimum.

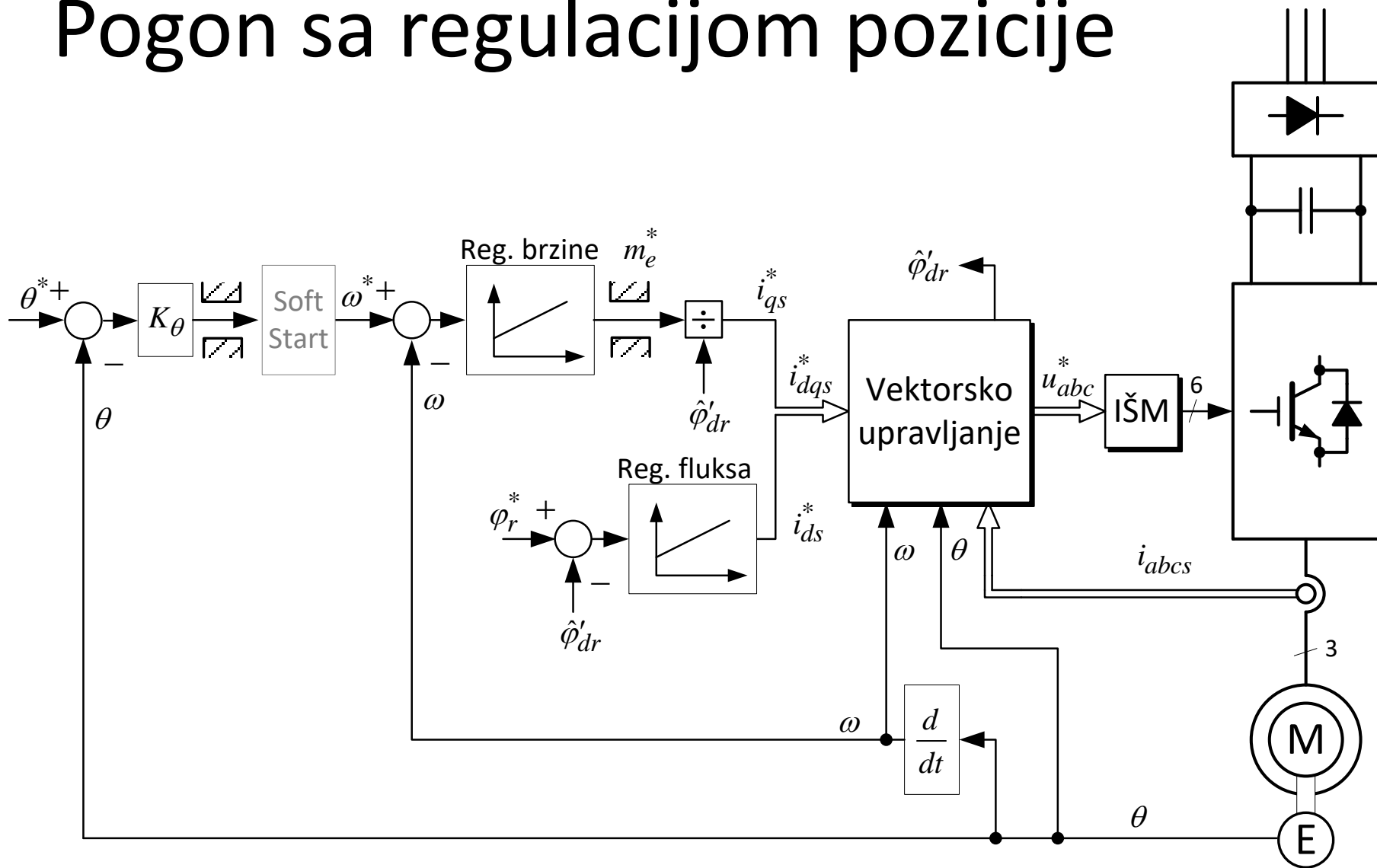
# Regulacija brzine



$$K_m = \frac{3}{2} \cdot P \cdot \frac{M}{L'_r}$$

Može se primeniti simetrični optimum.

# Pogon sa regulacijom pozicije



# Pregled karakteristika

## Prednosti:

- Brz i precizan odziv momenta motora.
- Optimalno iskorišćenje motora.
- Precizna regulacija brzine i pozicije.
- Koristi se isti energetski pretvarač.
- Povećana energetska efikasnost pri opterećenjima manjim od nazivnog.

## Nedostaci:

- Potrebno više davača struje (min. 2).
- Potreban davač na vratilu (enkoder, rezolver).
- Potrebno poznavanje parametara motora.
- Zbog složenijeg algoritma koristi se procesor viših performansi.

# Prevazilaženje nedostataka

## Nedostaci:

- Potrebno više davača struje (min. 2). ✓ Postoji mogućnost da se signali faznih struja motora rekonstruišu iz signala struje jednosmernog međukola. Davačima su pale cene.

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- Potreban davač na vratilu (enkoder, rezolver). ✓ Ukoliko su parametri motora tačno određeni i poznati, može se raditi bez davača na vratilu. Još uvek se ne postižu dobri rezultati na malim brzinama (učestanostima).

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- Poznavanje parametara motora. ✓ Izuzetno važno pri radu bez davača na vratilu. Parametri motora se određuju veoma precizno prilikom puštanja pogona u rad. U toku rada pogona se vrši kontinualno praćenje parametara motora – auto tuning.

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- Koristi se procesor viših performansi. ✓ Procesorima visokih performansi su pale cene. Ipak, ovo je često izgovor za veću cenu pogona.