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Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva

Upravljanje generatorskim i mrežnim frekvencijskim pretvaračem u vjetroagregatu

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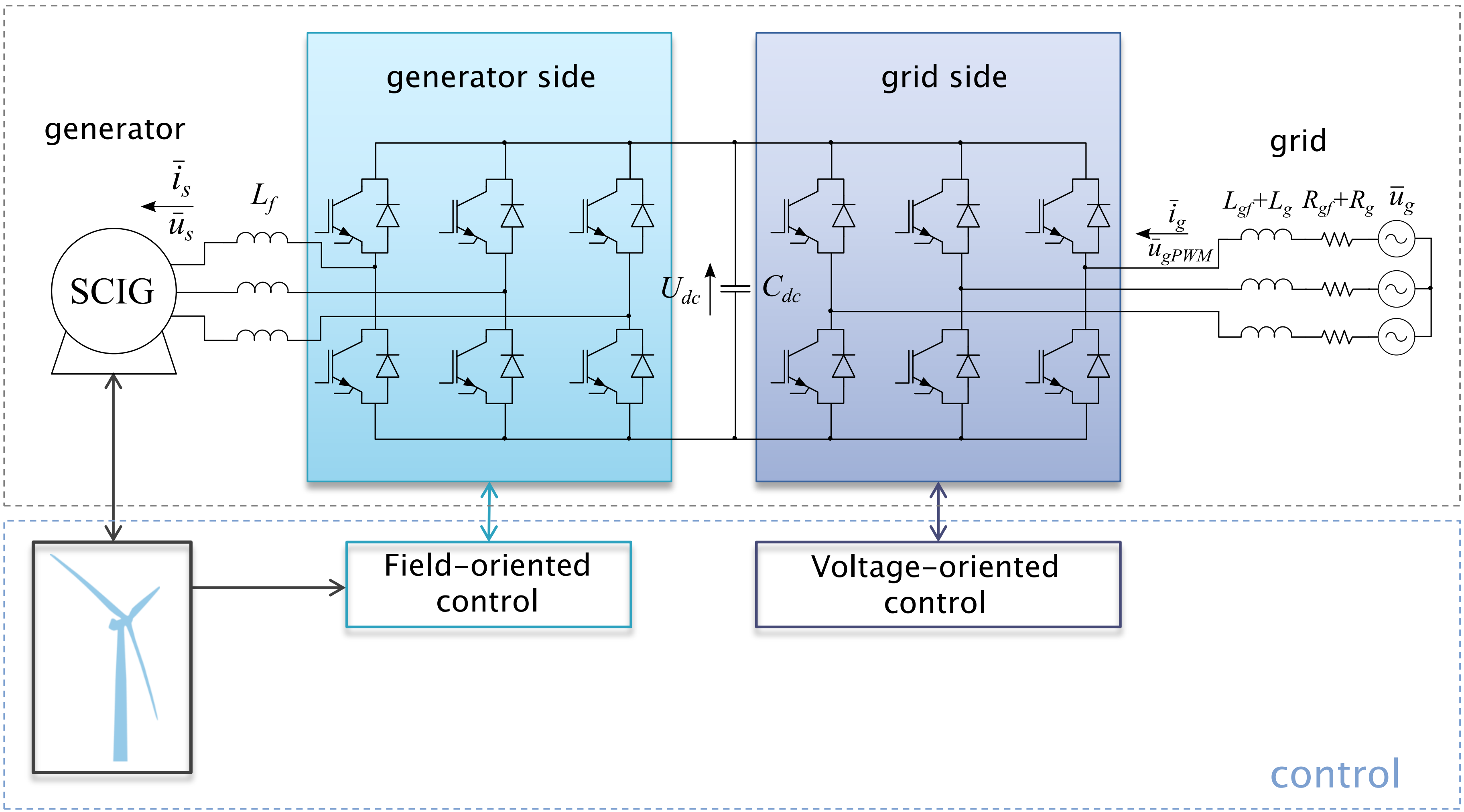
CEEStructHealth
FSB
KONČAR Electrical Engineering INSTITUTE
GF Građevinski fakultet
FER
LARES vjetar sunce vodik

Defence outline

- Generatori vjetroagregata
- Upravljanje generatorskim pretvaračem
- Estimacija veličina
- Upravljanje mrežnim pretvaračem
- Zaključak

Generatori vjetroagregata

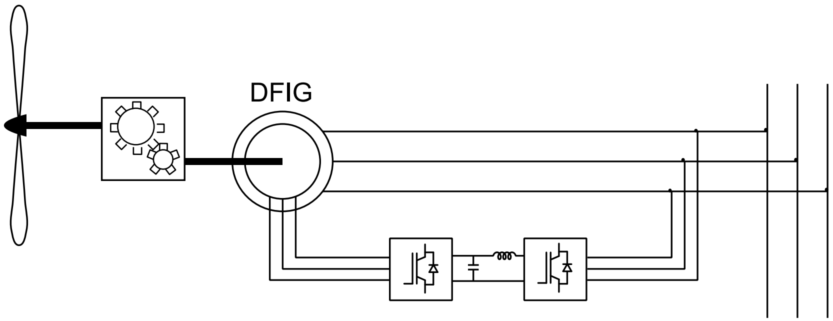
Wind turbine control



Wind turbine generators

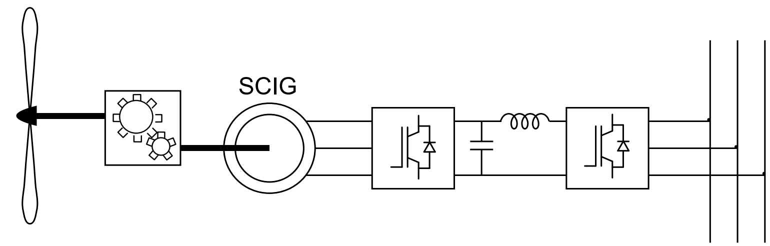
Asynchronous types

- Mature technology, usually up to 3 MW
- Fast rotating, gearbox required
- $p\omega_{rotor} = \omega_{source} - \omega_{slip}$



Doubly-Fed Induction Generator

- Vestas
- Sinovel
- Gamesa
- GE Energy



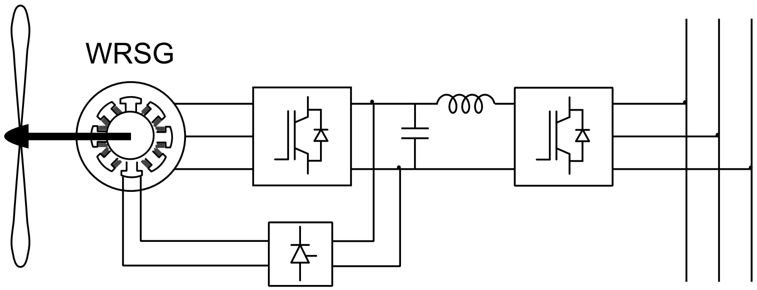
Squirrel-Cage Induction Generator

- Siemens

Wind turbine generators

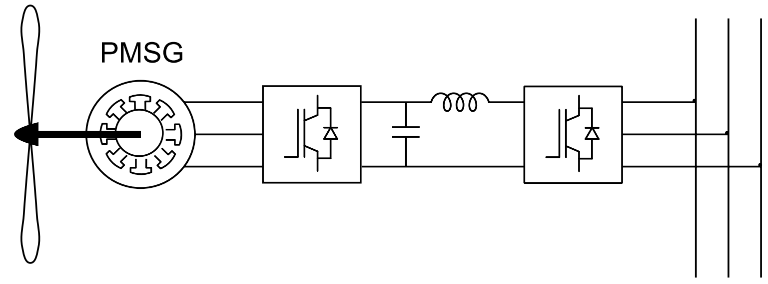
Synchronous types

- Newer technology, usually above 2,5 MW
- Slow rotating, direct-drive
- $p\omega_{rotor} = \omega_{source}$



Wound Rotor
Synchronous Generator

- Končar
- Enercon



Permanent-Magnet
Synchronous Generator

- Vestas
- Goldwind
- Gamesa
- GE Energy
- Siemens

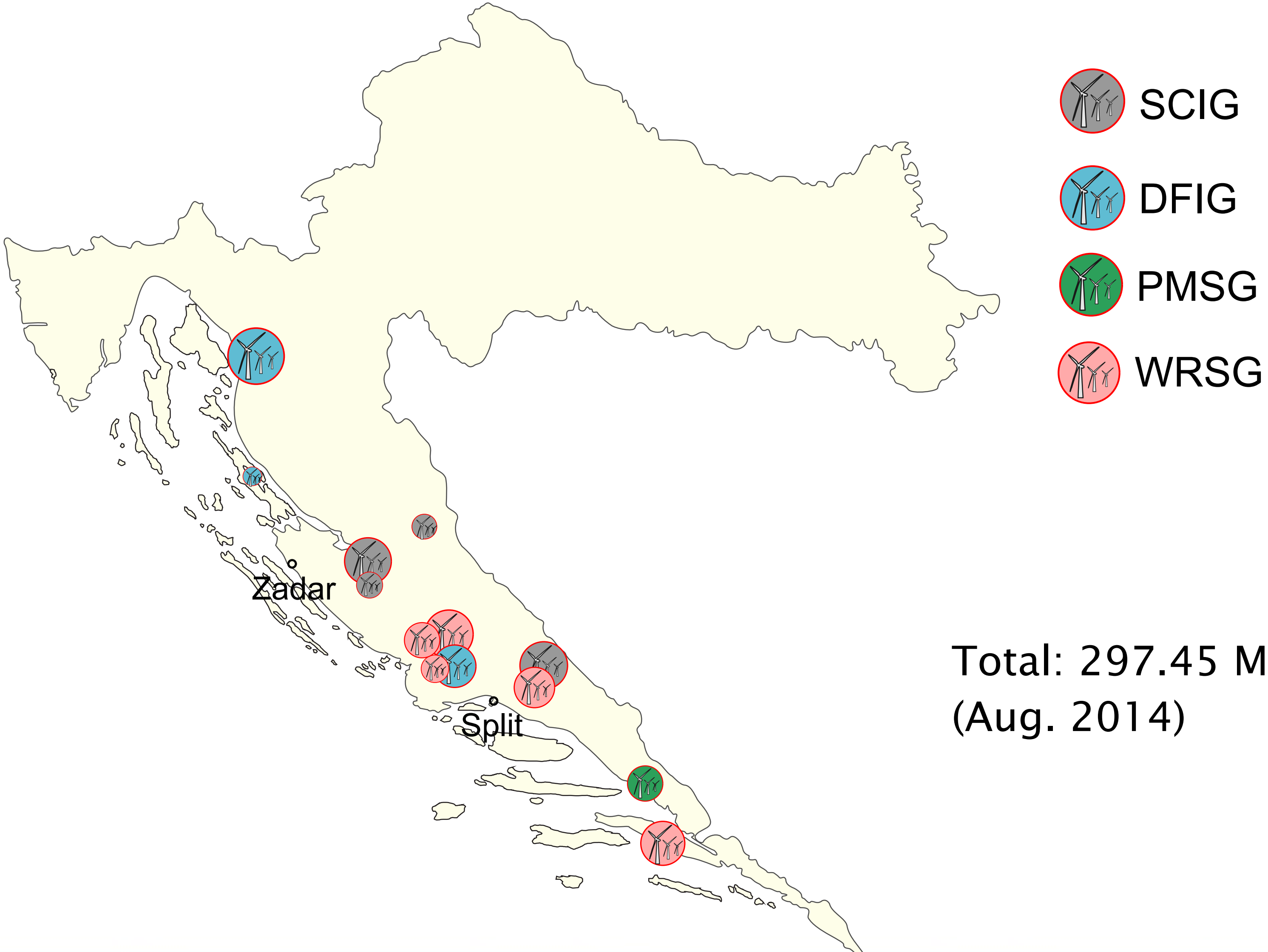
Wind farms in Croatia

Wind farm	Installed power (MW)	Region	Annual production (GWh)	Wind turbine models	Put in operation
VE Danilo	43	Šibensko-kninska županija	100	19 × Enercon E-82 – 2.3 MW	2014.
VE Vrataruša	42	Ličko-senjska županija	125	14 × Vestas V90 - 3 MW	2011.
VE Kamensko-Voštane	40	Splitsko-dalmatinska županija	114	14 × Siemens SWT-3.0-101 – 3 MW	2013.
VE Bruška (ZD2+ZD3)	36	Zadarska županija	122	16 × Siemens SWT-93 - 2,3 MW	2012.
VE Ponikve	34	Dubrovačko-neretvanska županija	100	16 x Enercon E-70 – 2,3 MW	2012.
VE Jelinak	30	Splitsko-dalmatinska županija	81	20 x Acciona AW-1500 – 1,5 MW	2013.
VE Pometeno Brdo	17.5	Splitsko-dalmatinska županija	30	15 × Končar KO-VA 57/1 – 1 MW +1 × Končar VA K80 – 2,5 MW	2012.
VE Trtar-Krtolin	11.2	Šibensko-kninska županija	28	14 × Enercon E-48 - 0,8 MW	2006.
VE Crno Brdo	10	Šibensko-kninska županija	27	7 × Leitwind LTW77 – 1,5 MW	2011.
VE Orlice	9.6	Šibensko-kninska županija	25	11 × Enercon (3 x E-48 – 0,8 MW + 8 × E-44 – 0,9 MW)	2009.
VE ZD 4 faza I	9.2	Zadarska županija	26	4 × Siemens SWT 93 – 2,3 MW	2013.
VE Velika Popina (ZD6)	9	Zadarska županija	26	4 × Siemens SWT 93 – 2,3 MW	2011.
VE Ravne	5.95	Zadarska županija	15	7 × Vestas V52 – 0,85 MW	2005.

Total 297.45 MW

DFIG	WRSG	SCIG	PMSG

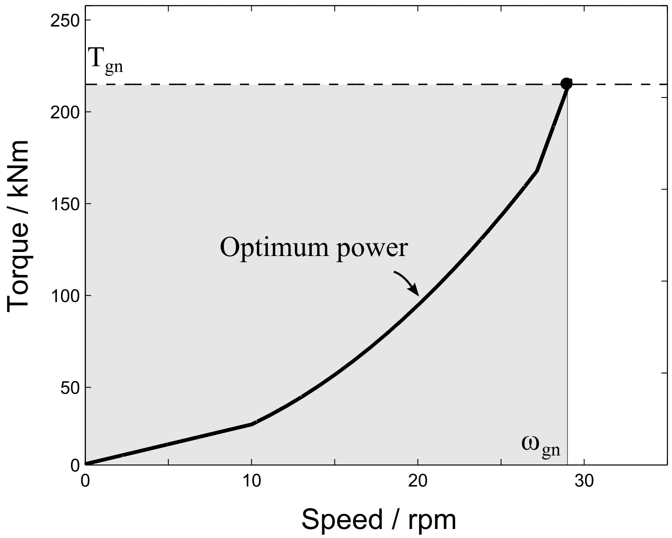
Wind farms in Croatia

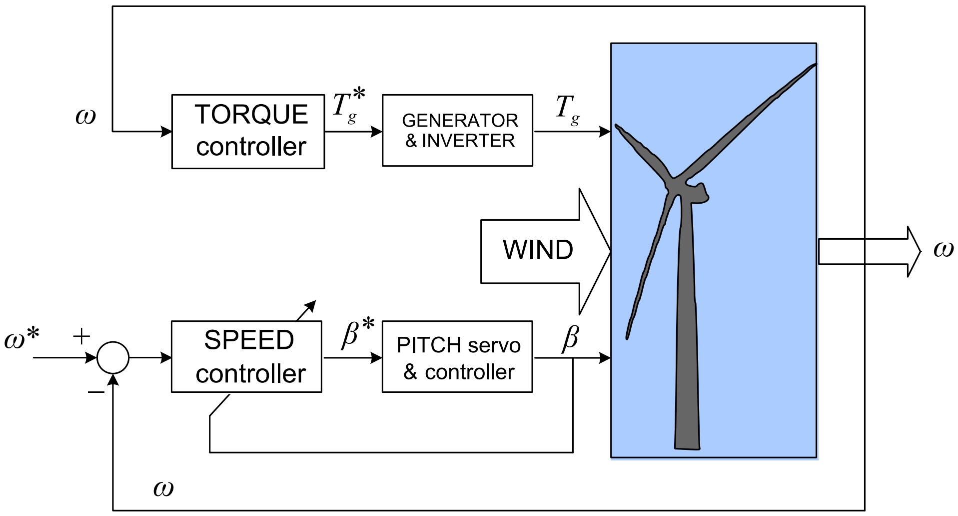


Total: 297.45 MW
(Aug. 2014)

Upravljanje generatorskim pretvaračem

Wind turbine control

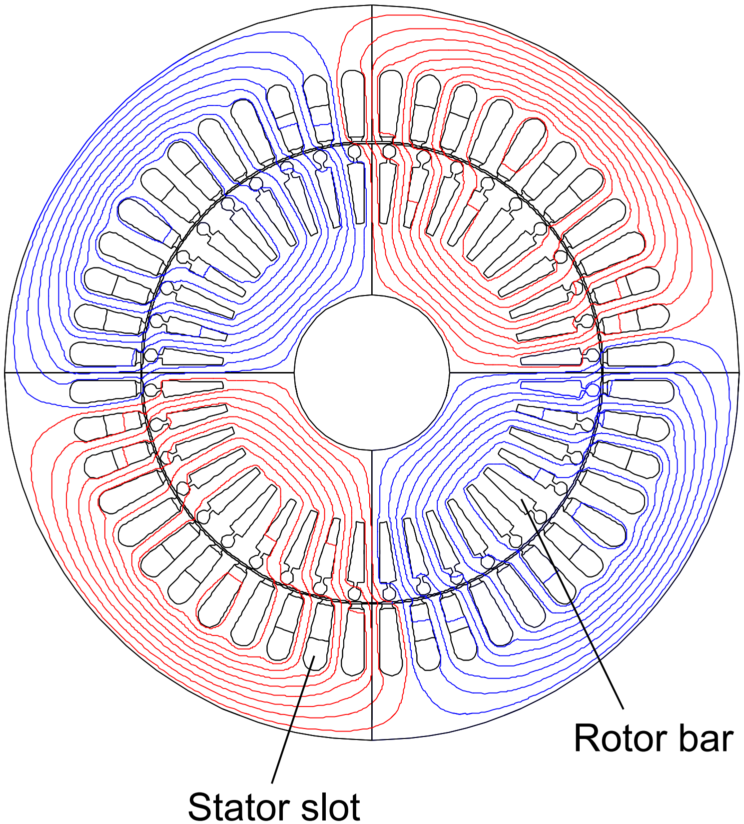




- Below rated wind speed – control via torque
  - $T_g^* = K_\lambda \omega^2$
- Above rated wind speed – control via pitch
  - Proportional-integral(-derivative) gain-scheduling controller

Generator control

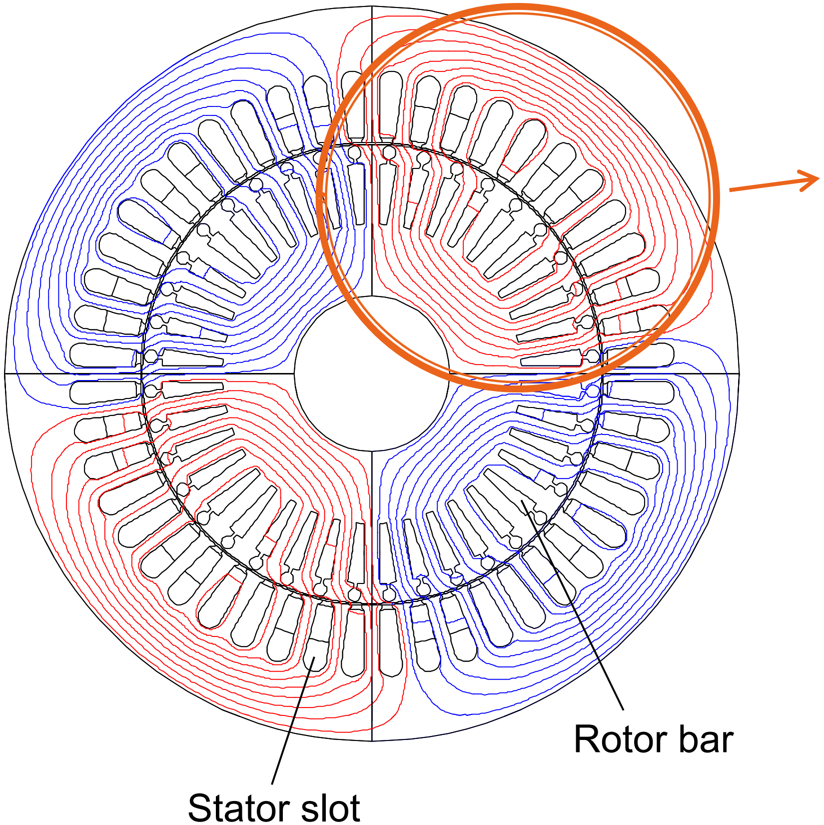
- Field-oriented control

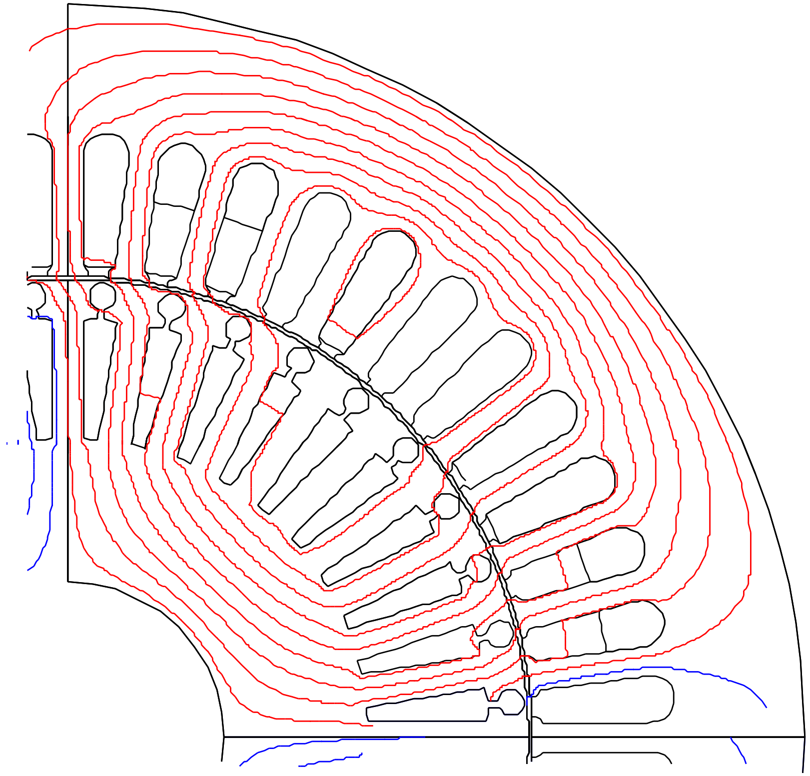


Source: Damir Žarko, Teorija električnih strojeva i transformatora

Generator control

- Field-oriented control

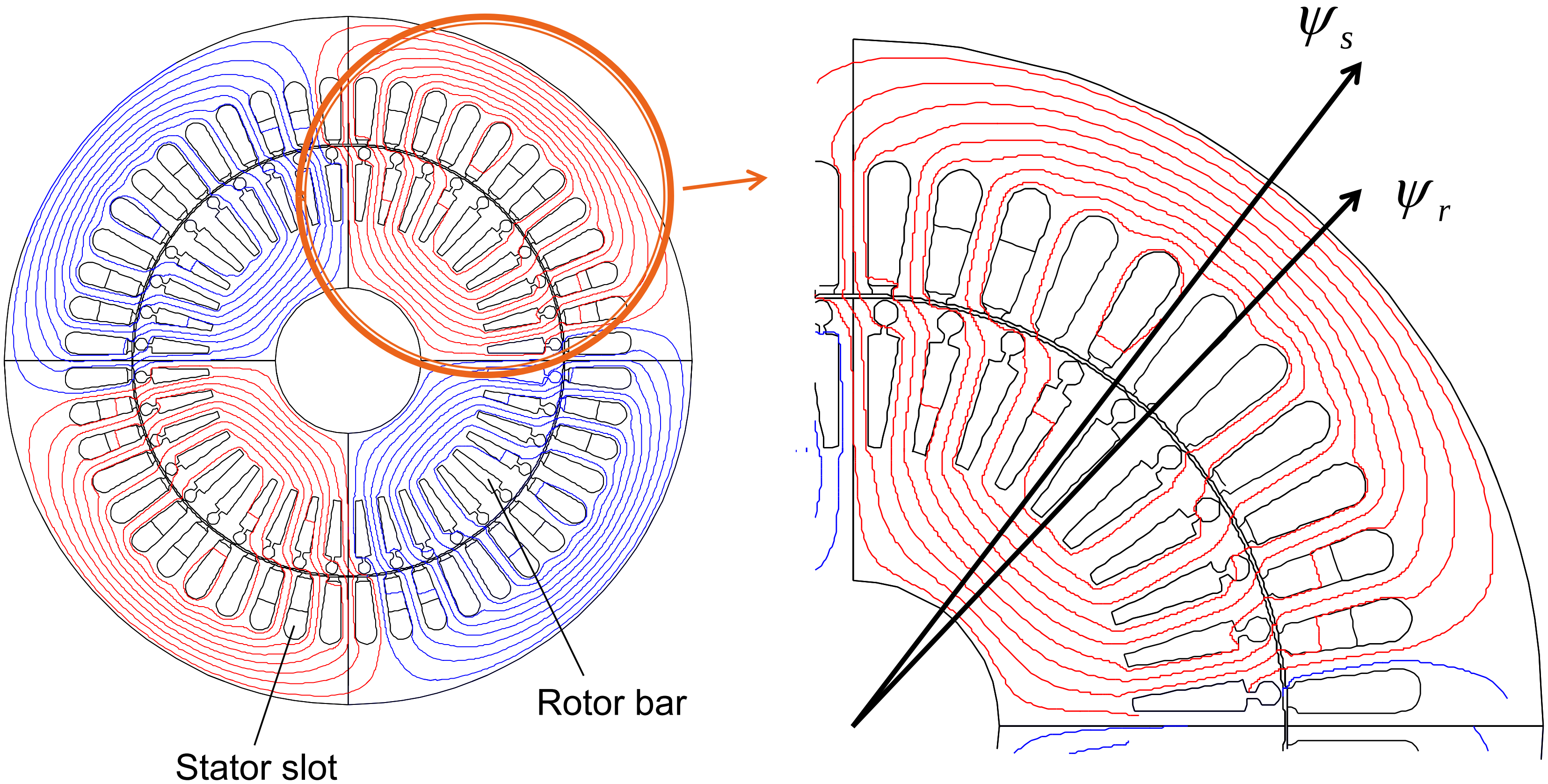




Source: Damir Žarko, Teorija električnih strojeva i transformatora

Generator control

- Field-oriented control



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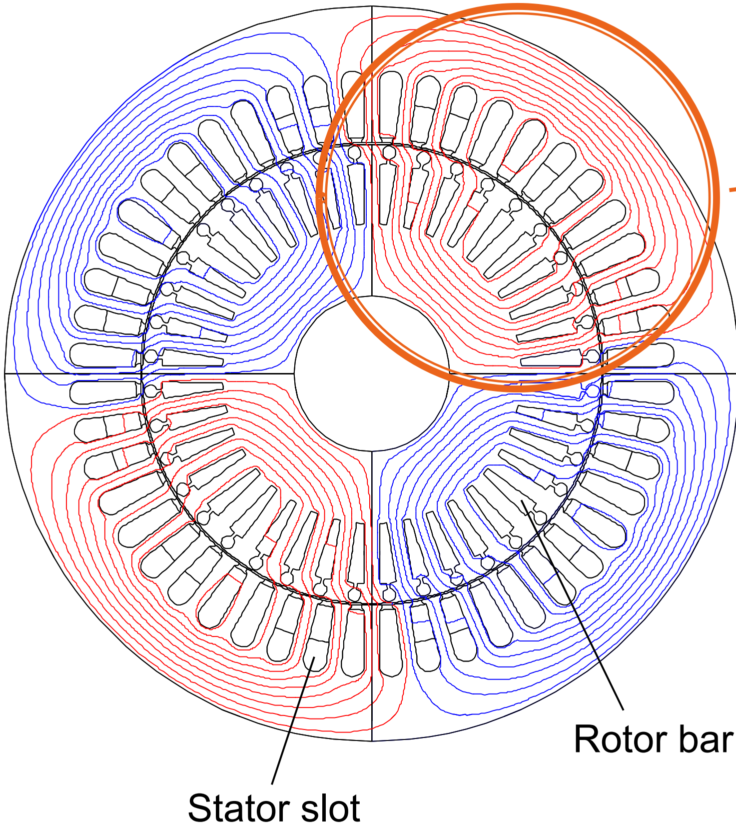
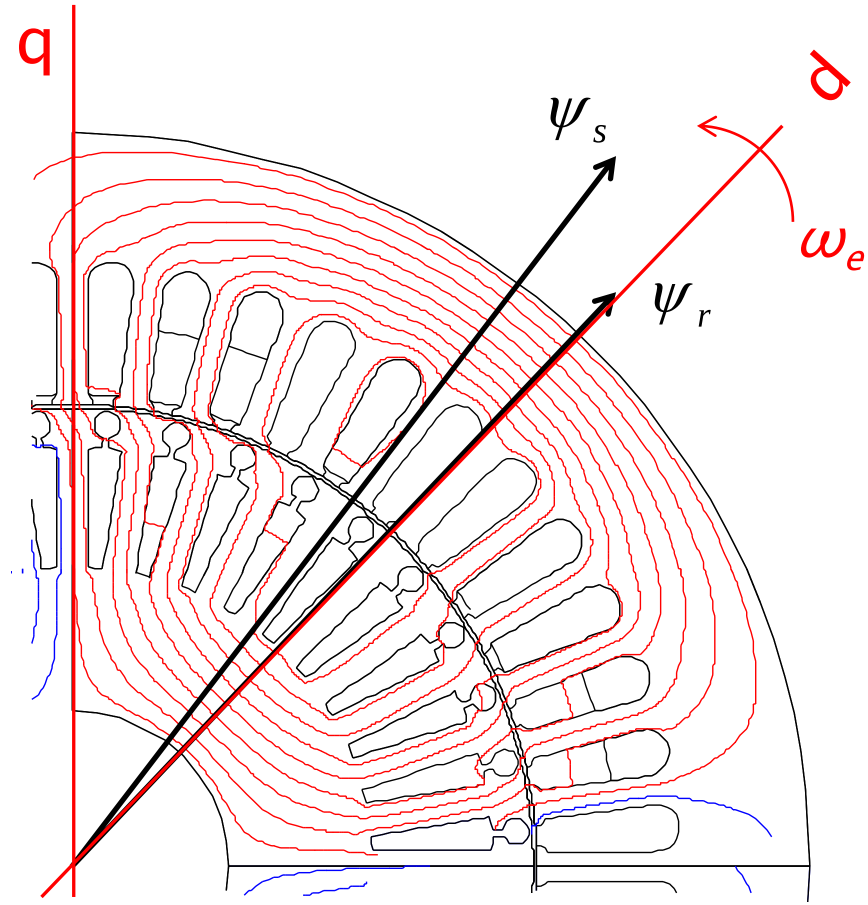
Generator control

- Field-oriented control





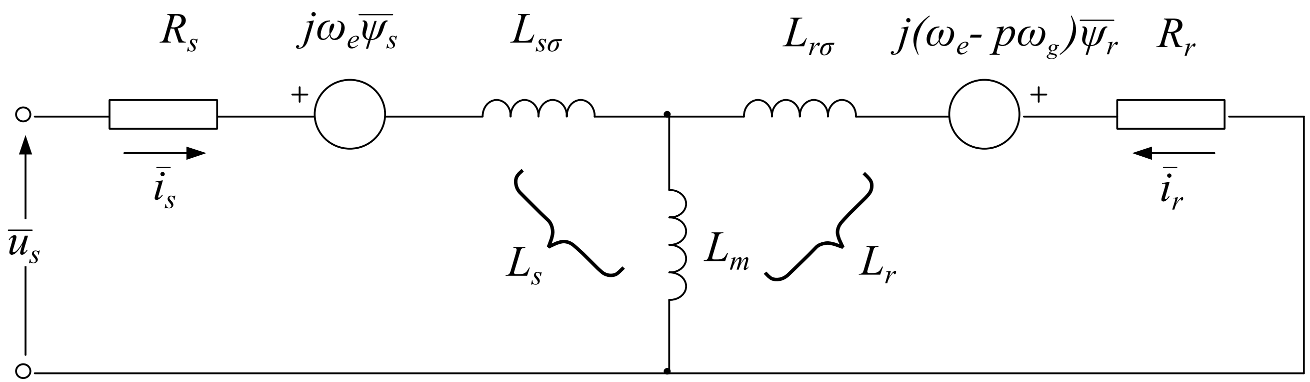
Source: Damir Žarko, Teorija električnih strojeva i transformatora

SCIG model

- SCIG model in *dq* rotating frame

$$\bar{u}_s = R_s \bar{i}_s + \frac{d\bar{\psi}_s}{dt} + j\omega_e \bar{\psi}_s$$

$$0 = R_r \bar{i}_r + \frac{d\bar{\psi}_r}{dt} + j(\omega_e - p\omega_g)\bar{\psi}_r$$



- Aligning with rotor flux linkage

$$\bar{\psi}_r = \psi_{rd} \qquad T_g = \frac{3}{2} p \frac{L_m^2}{L_r} i_{mr} i_{sq}$$

Generator control

- Voltage field-oriented control

$$u_{sd} = k_a i_{sd} + L_l \frac{di_{sd}}{dt} - \frac{1}{T_r}\frac{L_m^2}{L_r} i_{mr} - \omega_e L_l i_{sq}$$

$$u_{sq} = R_s i_{sq} + L_l \frac{di_{sq}}{dt} + \omega_e \frac{L_m^2}{L_r} i_{mr} + \omega_e L_l i_{sd}$$

$$k_s = R_s + \frac{L_m^2}{L_r^2} R_r$$

$$L_l = \sigma L_s = L_s - \frac{L_m^2}{L_r}$$

Generator control

- Voltage field-oriented control

$$u_{sd} = k_a i_{sd} + L_l \frac{di_{sd}}{dt} - \frac{1}{T_r}\frac{L_m^2}{L_r} i_{mr} - \omega_e L_l i_{sq}$$

$$u_{sq} = R_s i_{sq} + L_l \frac{di_{sq}}{dt} + \omega_e \frac{L_m^2}{L_r} i_{mr} + \omega_e L_l i_{sd}$$

$$k_s = R_s + \frac{L_m^2}{L_r^2} R_r$$

$$L_l = \sigma L_s = L_s - \frac{L_m^2}{L_r}$$

- Decoupling

$$u_{sd} + \Delta u_{sd} = k_s i_{sd} + L_l \frac{di_{sd}}{dt}$$

$$u_{sq} + \Delta u_{sq} = R_s i_{sq} + L_l \frac{di_{sq}}{dt}$$

$$\frac{T_g(s)}{T_g^*(s)} = \frac{1}{1 + \tau \cdot s}$$

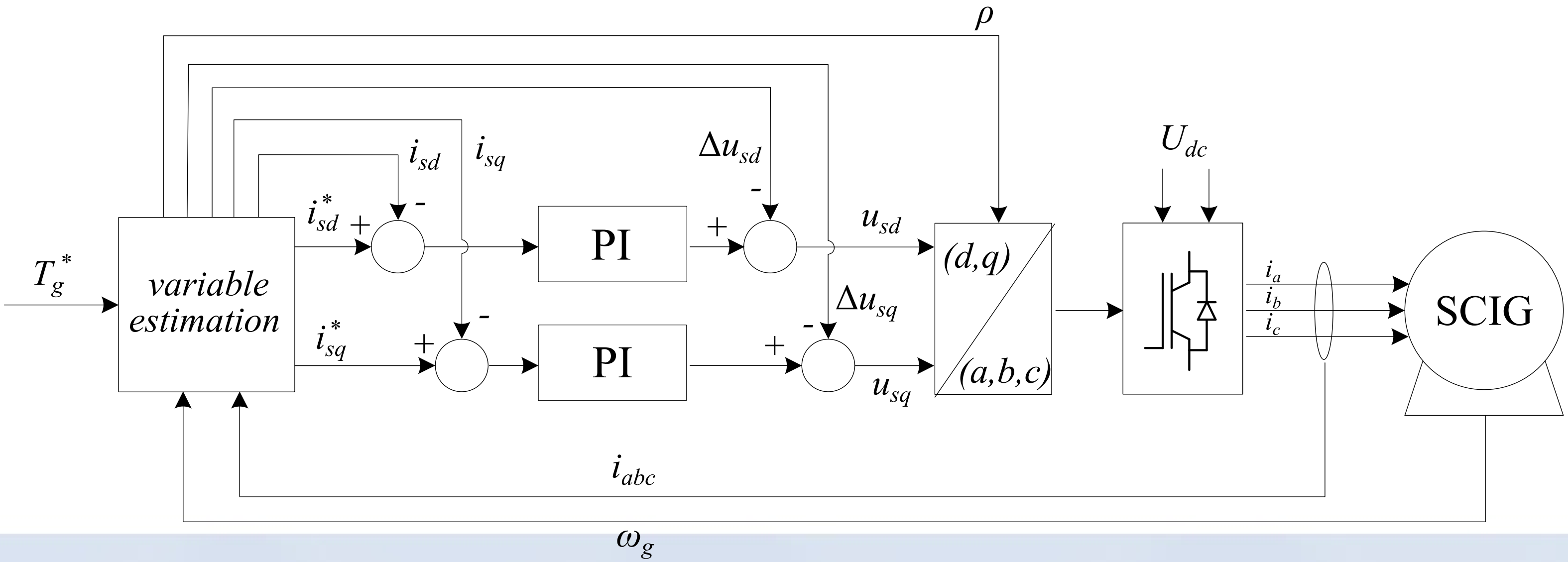
Field-oriented control

- PI current controllers:

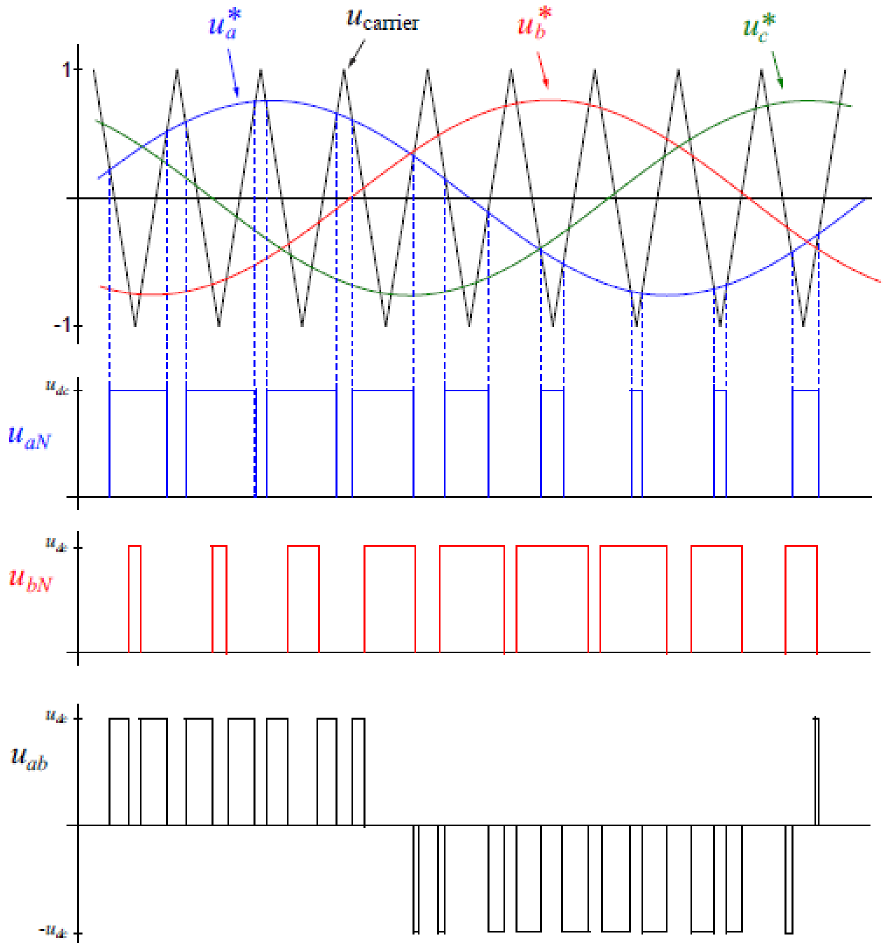
$$T_{Id} = \frac{\sigma L_s}{k_a}, \qquad T_{Iq} = \frac{\sigma L_s}{R_s}$$

- Closed loop transfer function:

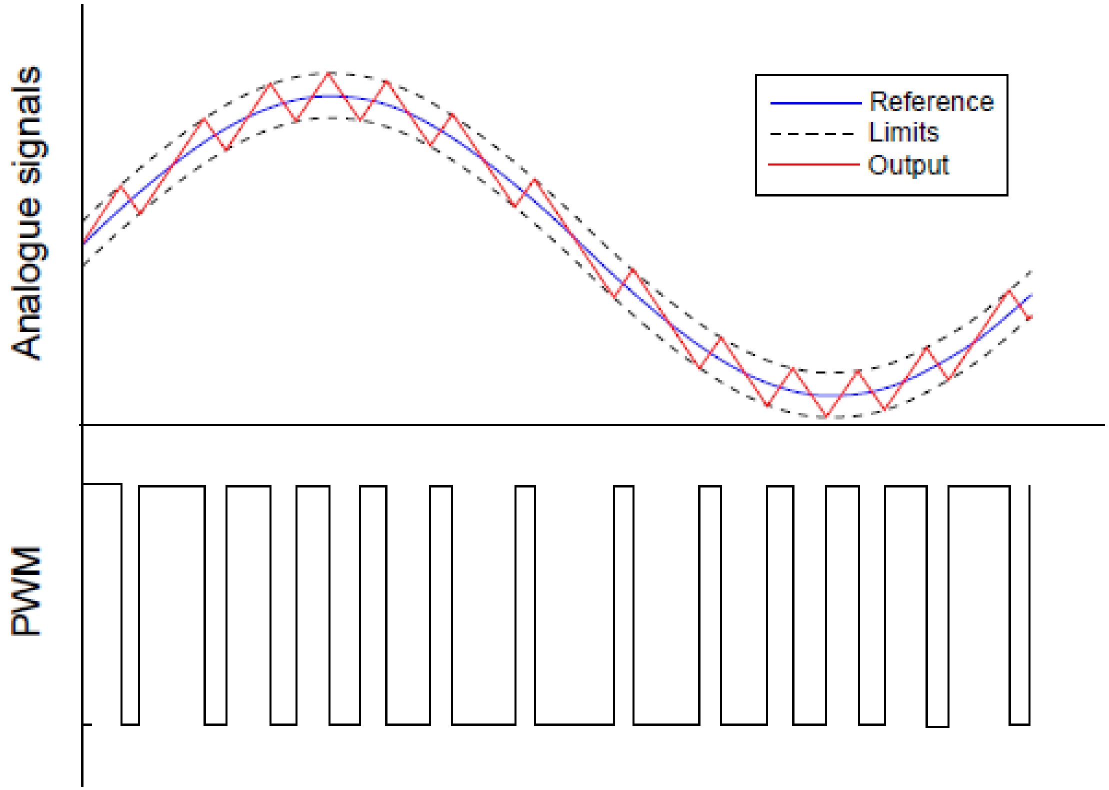
$$\frac{T_g(s)}{T_g^*(s)} = \frac{i_{sq}(s)}{i_{sq}^*(s)} = \frac{1}{1+\tau \cdot s} \qquad \tau = \frac{\sigma L_s}{K_r} \approx 100\mu s$$



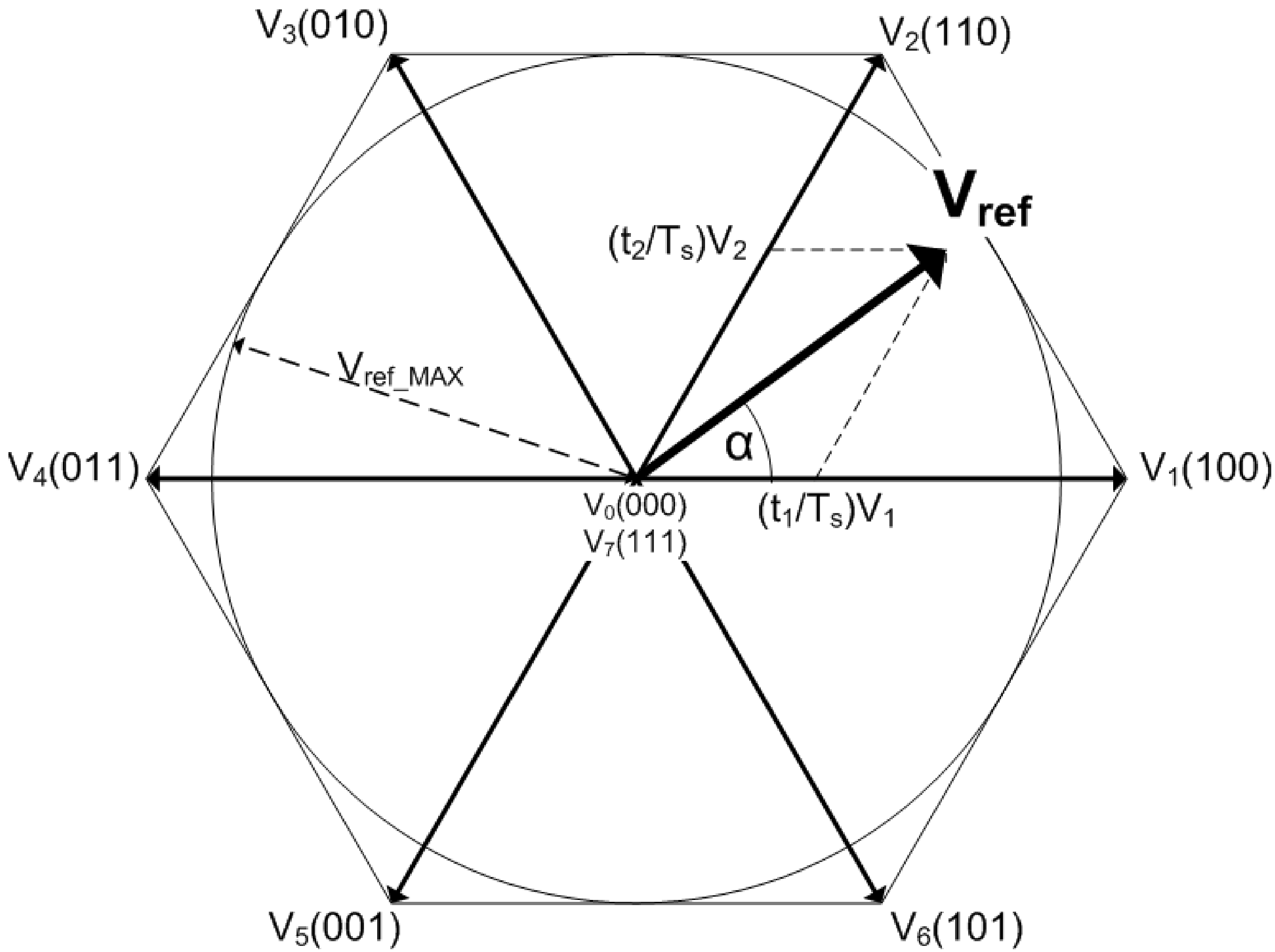
Pulse-width modulation



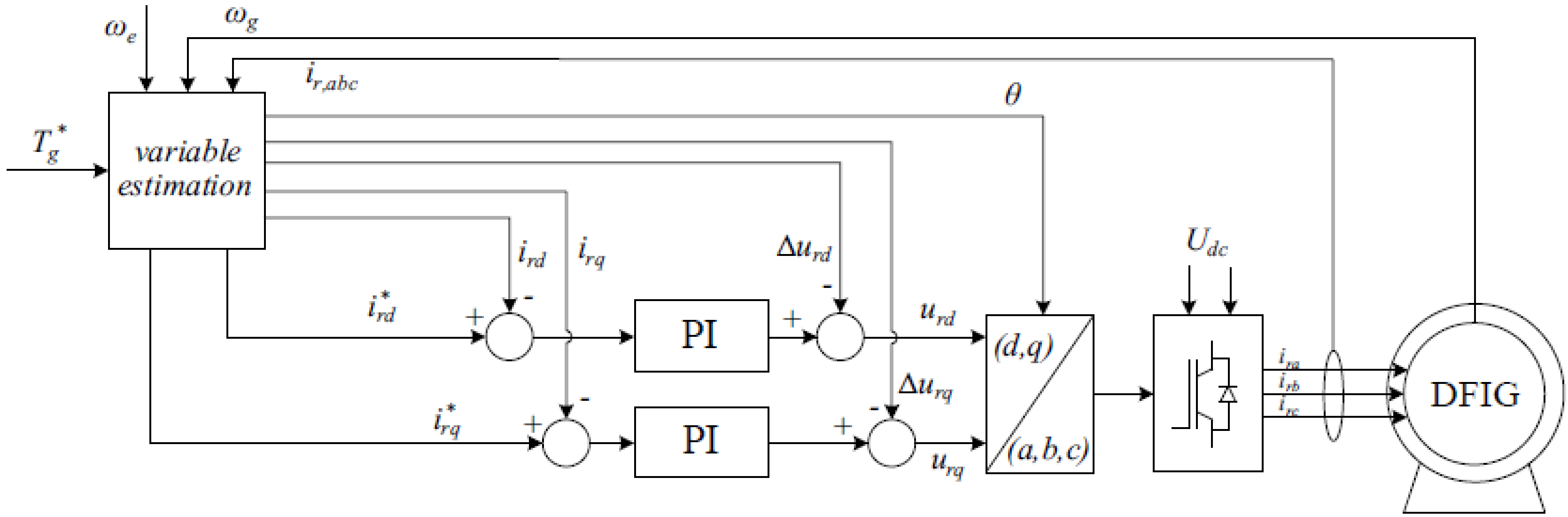
Hystheresis or „bang-bang” PWM



Space vector modulation

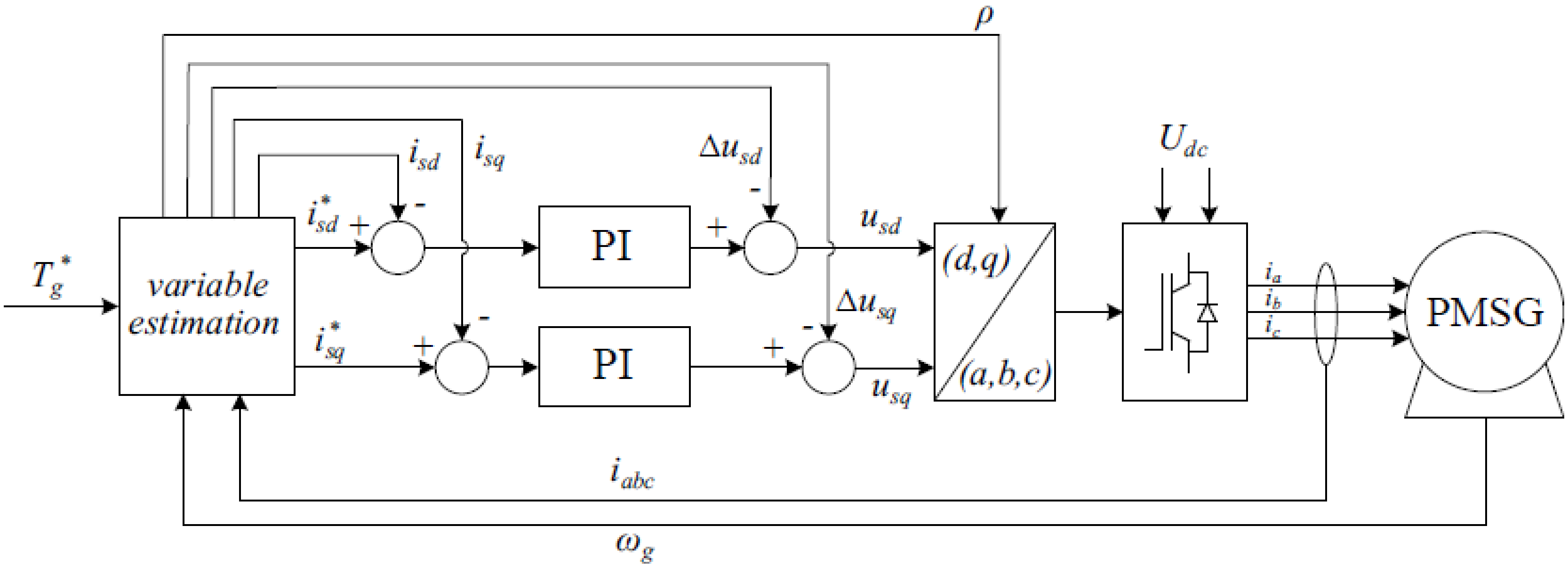


DFIG type



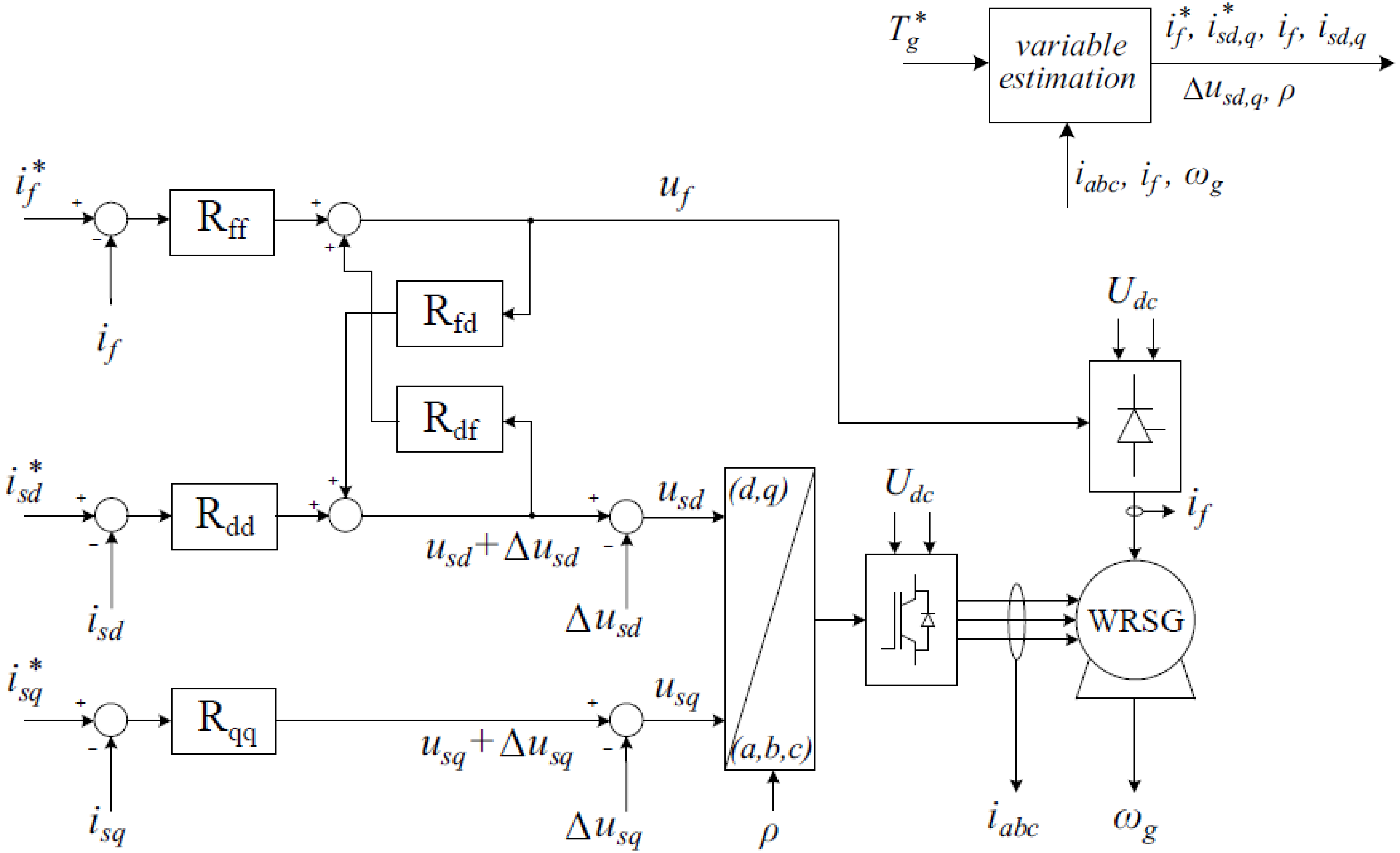
ω_e
ω_g
$i_{r,abc}$
θ
T_g^*
variable estimation
i_{rd}
i_{rq}
Δu_{rd}
U_{dc}
i_{rd}^*
PI
u_{rd}
(d,q)
(a,b,c)
Δu_{rq}
i_{rq}^*
PI
u_{rq}
DFIG

PMSG type



ρ
i_{sd}
i_{sq}
Δu_{sd}
U_{dc}
T_g^*
variable estimation
i_{sd}^*
i_{sq}^*
PI
PI
u_{sd}
Δu_{sq}
u_{sq}
(d,q)
(a,b,c)
i_a
i_b
i_c
PMSG
i_{abc}
ω_g

WRSG type



Constrained optimal control

- Model predictive direct current control

$$J=\sum_{k=0}^{N} r_k\left(i_{sd}(k+1)-i_{sd}^{*}\right)^2+\sum_{k=0}^{N}\lambda_d\left(u_{cd}(k)-u_{cd}(k-1)\right)^2+\sum_{k=0}^{N} q_k\left(i_{sq}(k+1)-i_{sq}^{*}\right)^2+$$

$$\sum_{k=0}^{N}\lambda_q\left(u_{cq}(k)-u_{cq}(k-1)\right)^2$$

$$u_{cd,q}=u_{sd,q}+\Delta u_{sd,q}$$

Subject to: $u_{sd}^2+u_{sq}^2\le\left(\frac{u_{dc}}{\sqrt{3}}\right)^2$

$$0\le\psi_{sd}\le\psi_{sdn}$$

Constrained optimal control

- Model predictive direct current control

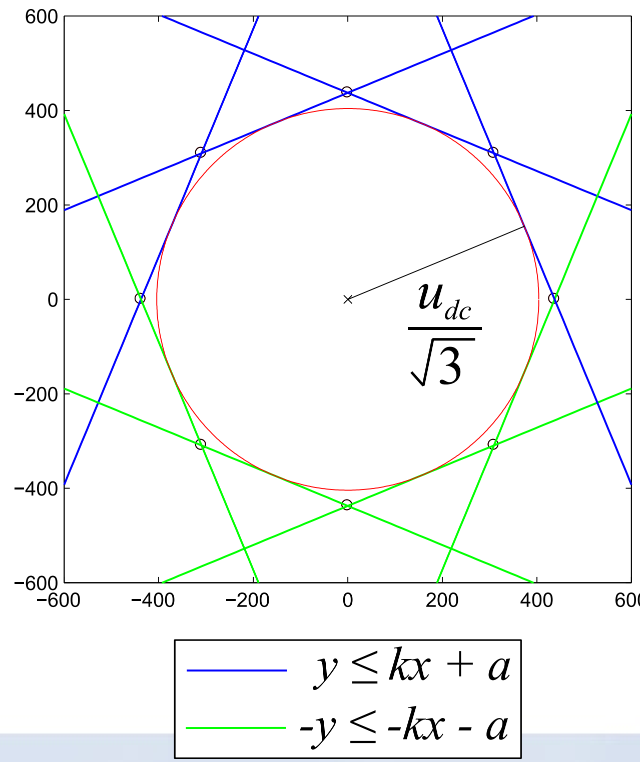
$$J = \sum_{k=0}^{N} r_k \left(i_{sd}(k+1) - i_{sd}^{*}\right)^2 + \sum_{k=0}^{N} \lambda_d \left(u_{cd}(k) - u_{cd}(k-1)\right)^2 + \sum_{k=0}^{N} q_k \left(i_{sq}(k+1) - i_{sq}^{*}\right)^2 +$$

$$\sum_{k=0}^{N} \lambda_q \left(u_{cq}(k) - u_{cq}(k-1)\right)^2$$

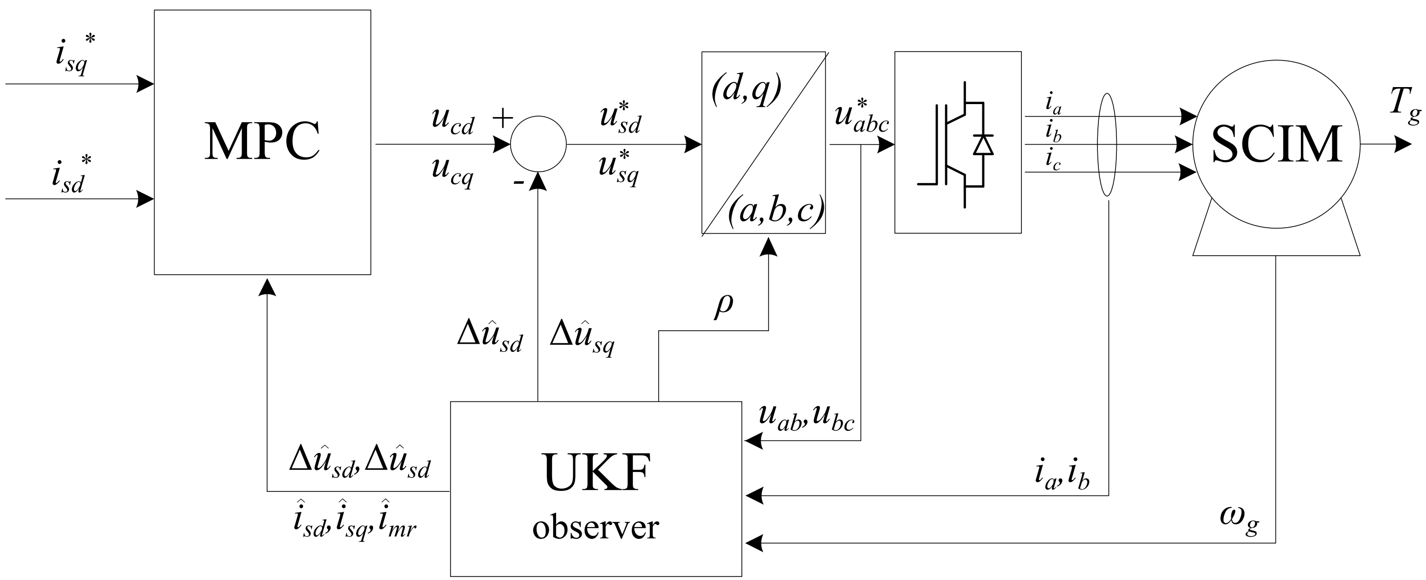
$$u_{cd,q} = u_{sd,q} + \Delta u_{sd,q}$$

Subject to: $$u_{sd}^2 + u_{sq}^2 \le \left(\frac{u_{dc}}{\sqrt{3}}\right)^2$$

$$0 \le \psi_{sd} \le \psi_{sdn}$$

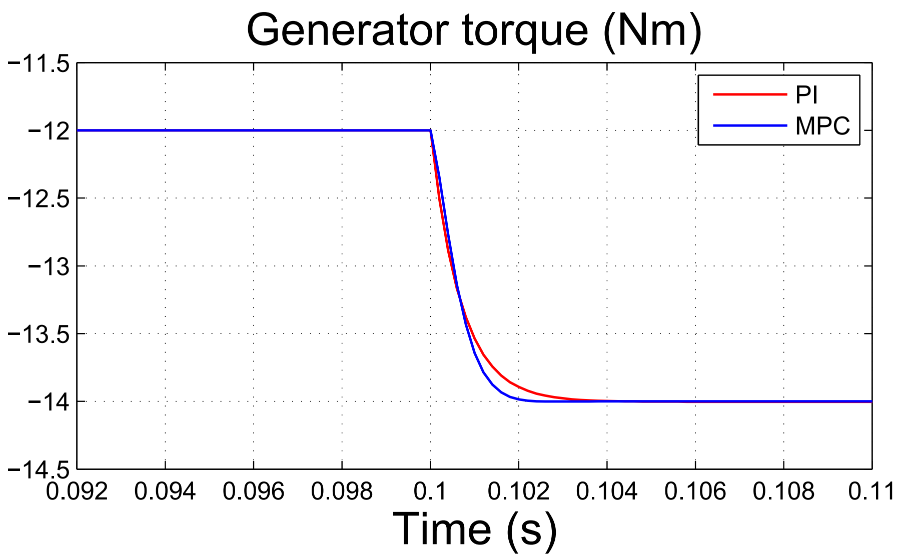


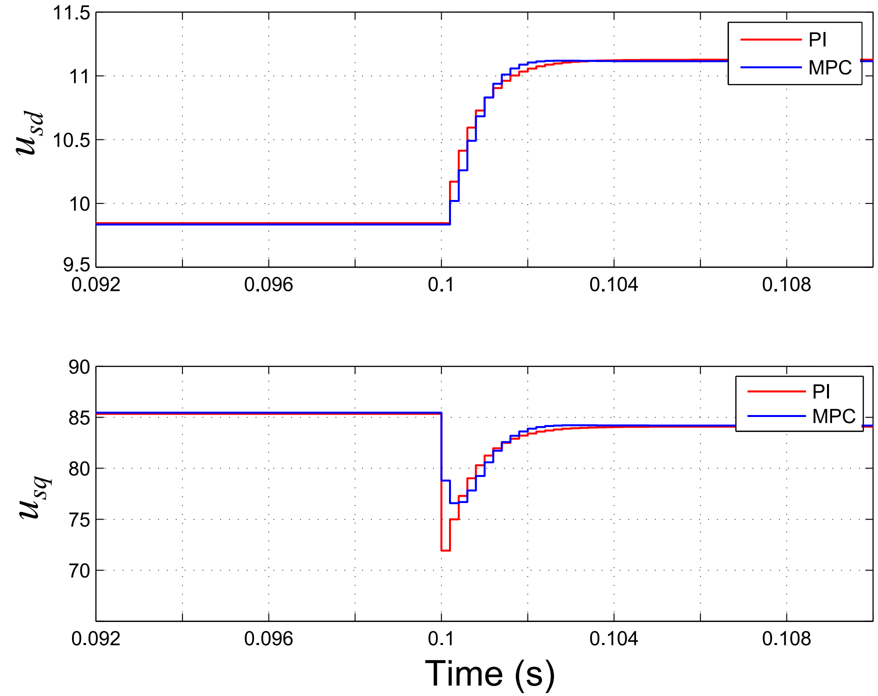
Model predictive direct current control



$$x = \begin{bmatrix} i_{sd} \\ i_{sq} \\ u_{cd}^{k-1} \\ u_{cq}^{k-1} \end{bmatrix} \qquad u = \begin{bmatrix} u_{cd}^{k} - u_{cd}^{k-1} \\ u_{cq}^{k} - u_{cq}^{k-1} \end{bmatrix} \qquad y = \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}$$

Simulation results



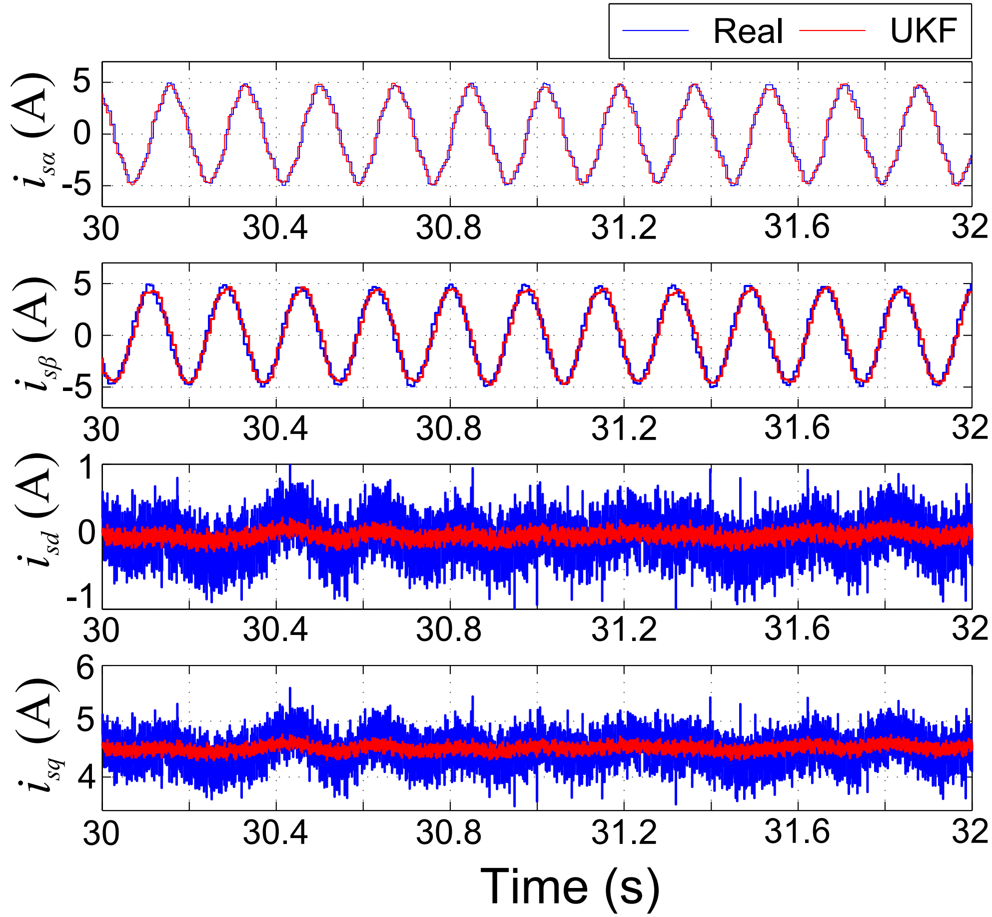


- Optimal and constrained
- Can be easily extended with other constraints

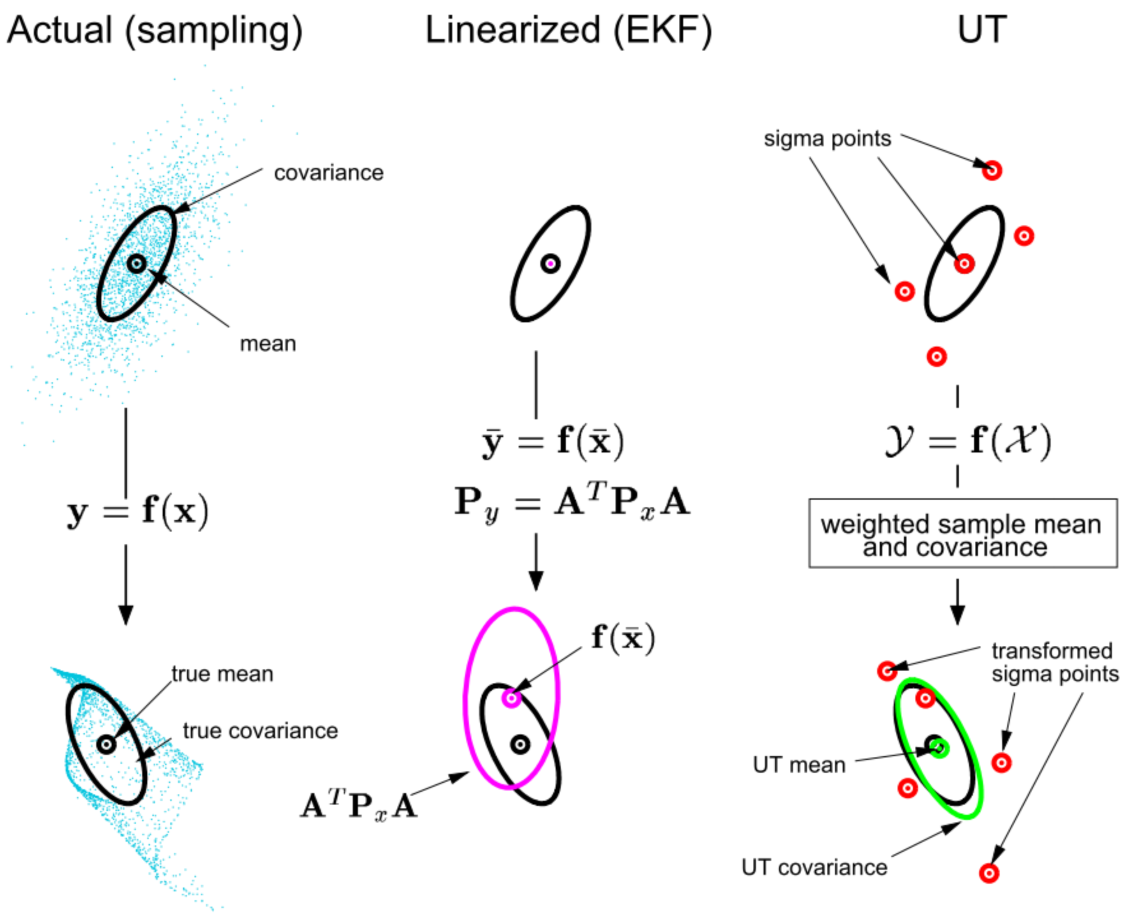
Estimacija veličina

Unscented Kalman filter

- Fundamental component extraction (PMSG case)



Unscented Kalman filter



S. Haykin, *Kalman Filtering and Neural Networks*, 2001

- Nonlinear filter
- Second order of Taylor series (or more)
- Nonlinear model can be directly used
- Runge–Kutta numerical integration

State and parameter estimation

$$\frac{\mathrm{d}i_{sd}}{\mathrm{d}t} = w_1\left(u_{sd} + \Delta u_{sd}(x,u,w) - w_2 i_{sd}\right)$$

$$\frac{\mathrm{d}i_{sq}}{\mathrm{d}t} = w_1\left(u_{sq} + \Delta u_{sq}(x,u,w) - w_3 i_{sq}\right)$$

$$\frac{\mathrm{d}i_{mr}}{\mathrm{d}t} = w_4\left(i_{sd} - i_{mr}\right)$$

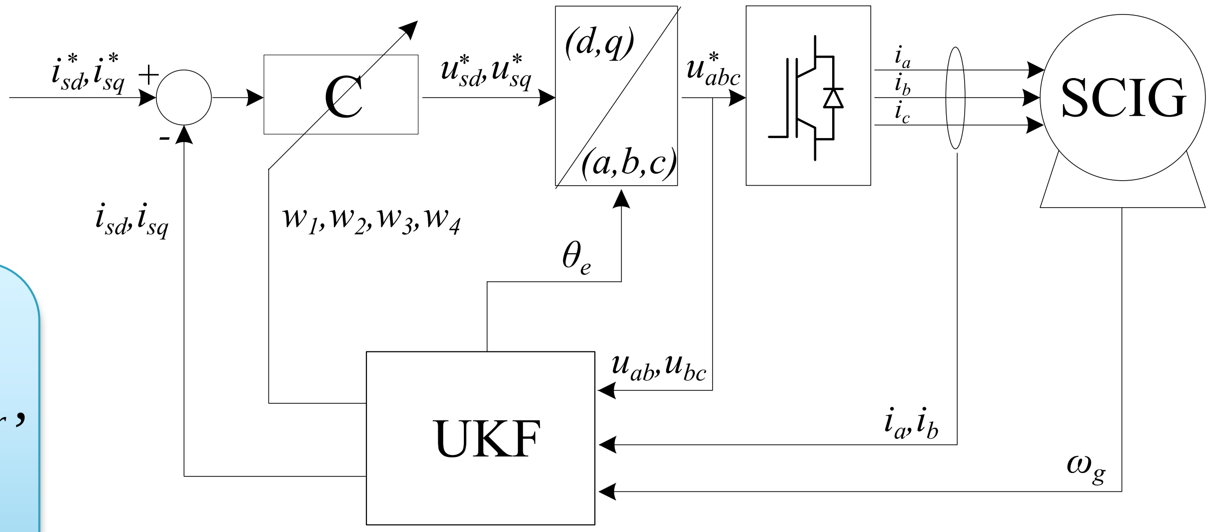
$$\frac{\mathrm{d}\theta_e}{\mathrm{d}t} = p\omega_g + w_4\frac{i_{sq}}{i_{mr}}$$

- Dual Unscented Kalman filter (UKF)
- Runge–Kutta 4th order

Parameters:

$$w_1 = \frac{1}{L_l},\quad w_2 = R_s + \frac{L_m^2}{L_r^2}R_r,$$

$$w_3 = R_s,\quad w_4 = \frac{1}{T_r}$$



Nonlinear system observability

$$L_F(H) = \nabla H \cdot F = \left[\frac{\partial H}{\partial x_1}, \cdots, \frac{\partial H}{\partial x_n}\right] \cdot \begin{bmatrix} f_1(x) \\ \vdots \\ f_n(x) \end{bmatrix}$$

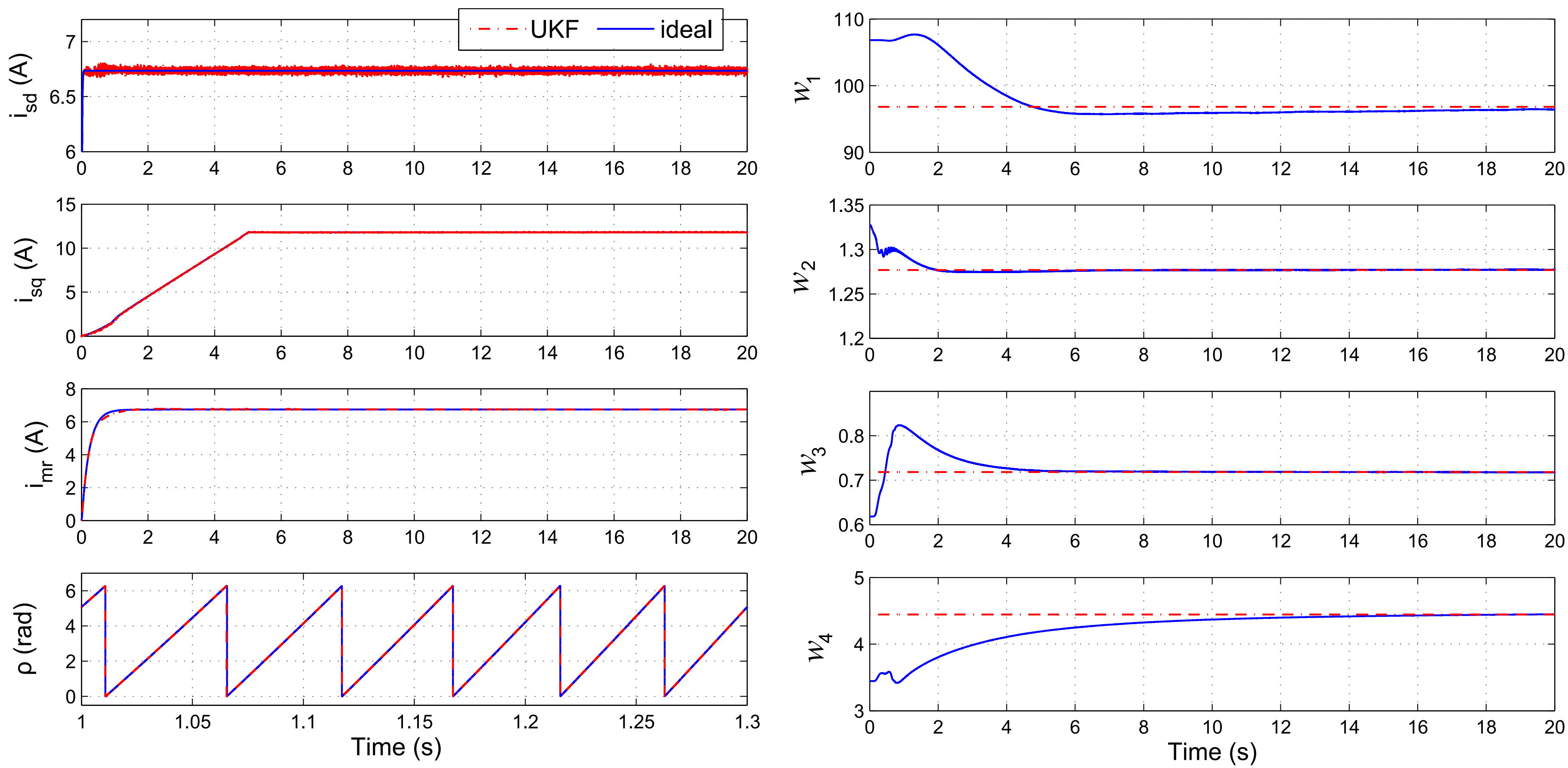
$$L_F^i(H) = \frac{\partial}{\partial x}\left[L_F^{i-1}(H)\right] \cdot F, \qquad i = 1, ..., n-1,$$

$$\mathbf{L} = \begin{bmatrix} L_F^0(h_1) & \cdots & L_F^0(h_m) \\ \vdots & \ddots & \vdots \\ L_F^{n-1}(h_1) & \cdots & L_F^{n-1}(h_m) \end{bmatrix}$$

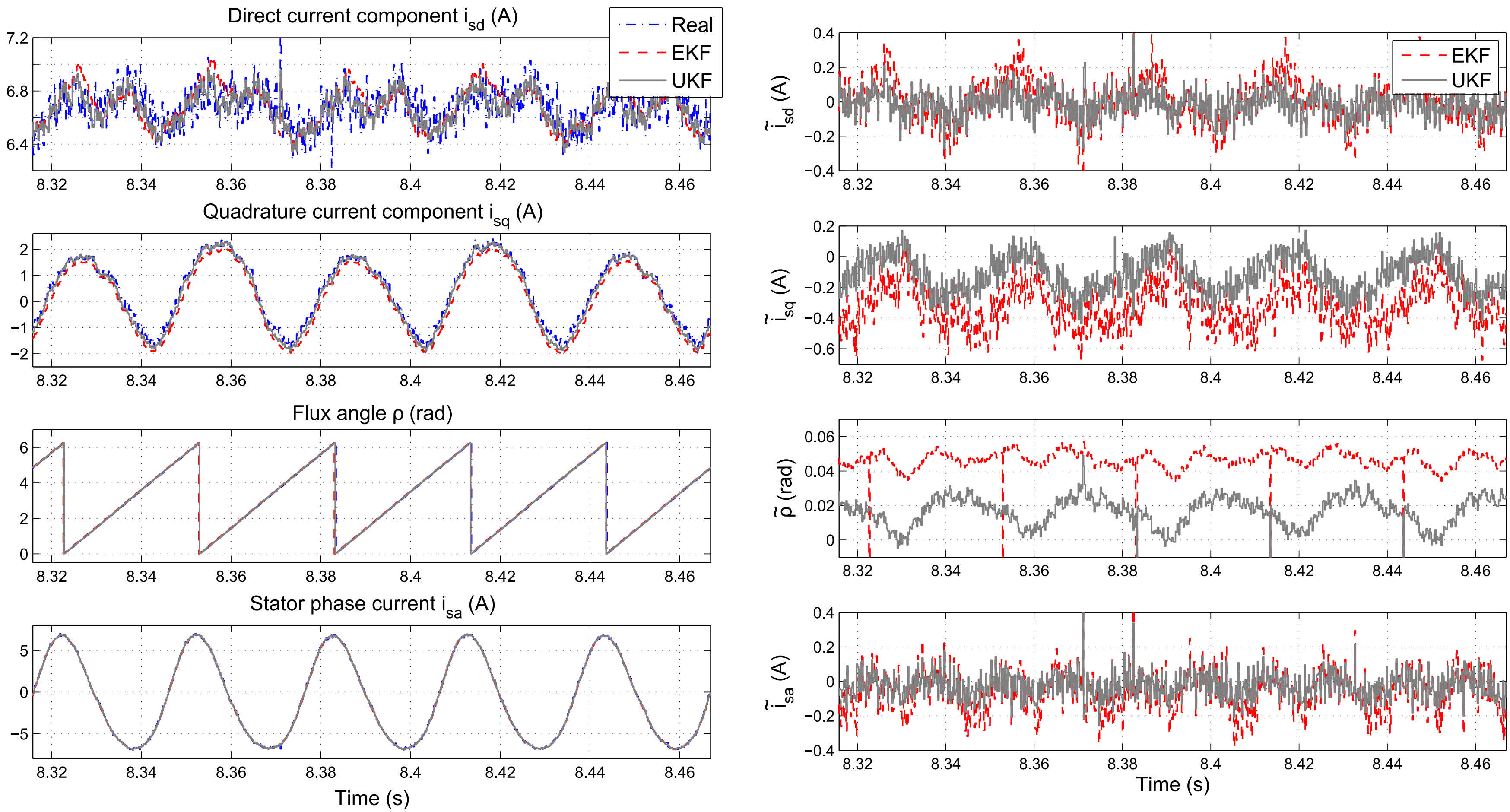
System is observable if gradient matrix of L (dL) has full rank

$$\det(\mathbf{dL}_s)|_{\omega_e=0} = \frac{3L_m^4(i_{mr} - i_{sd})}{4T_r^2(L_m^2 - L_r L_s)^2}$$

State and parameter estimation

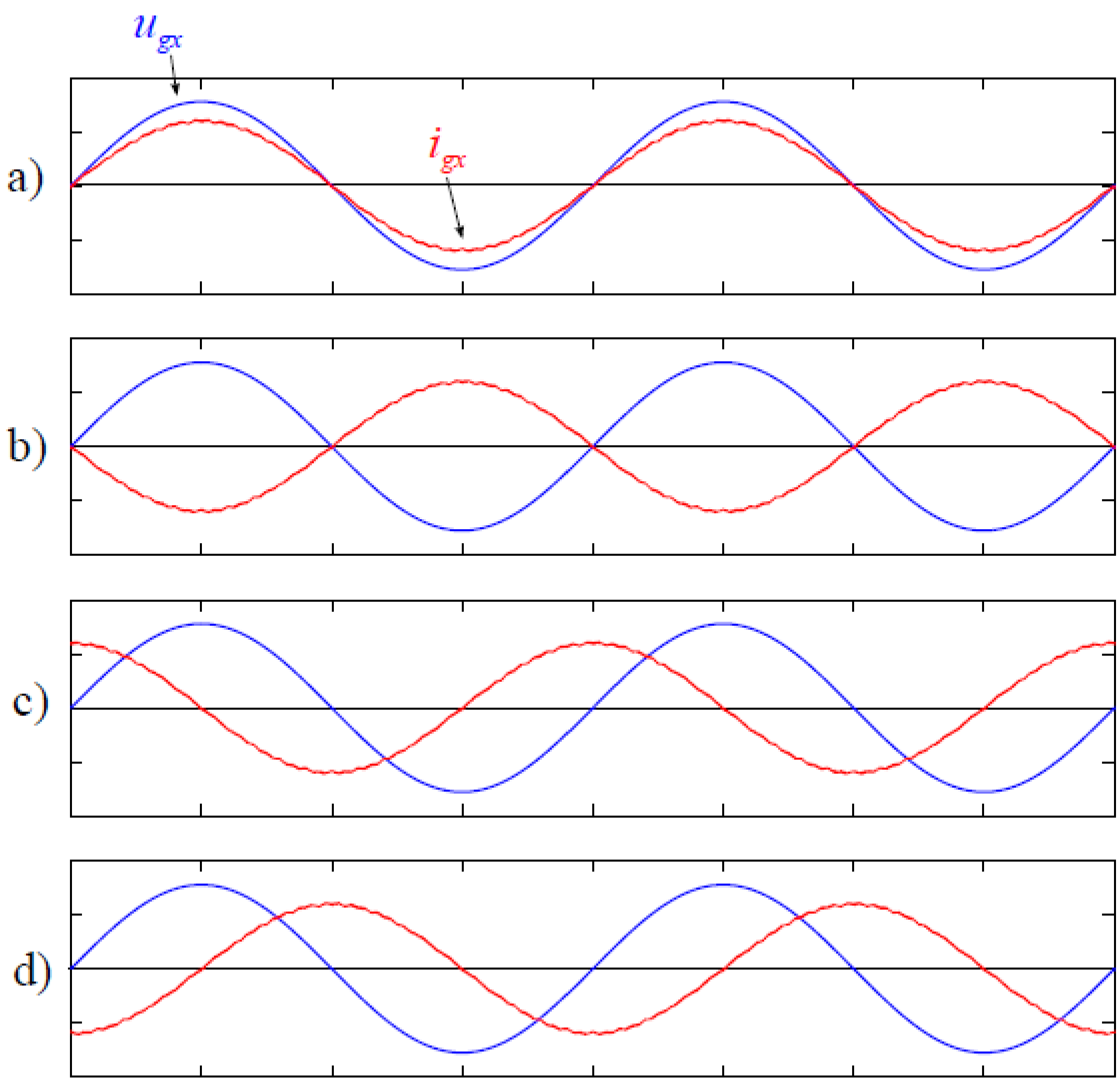


Comparison of UKF and EKF



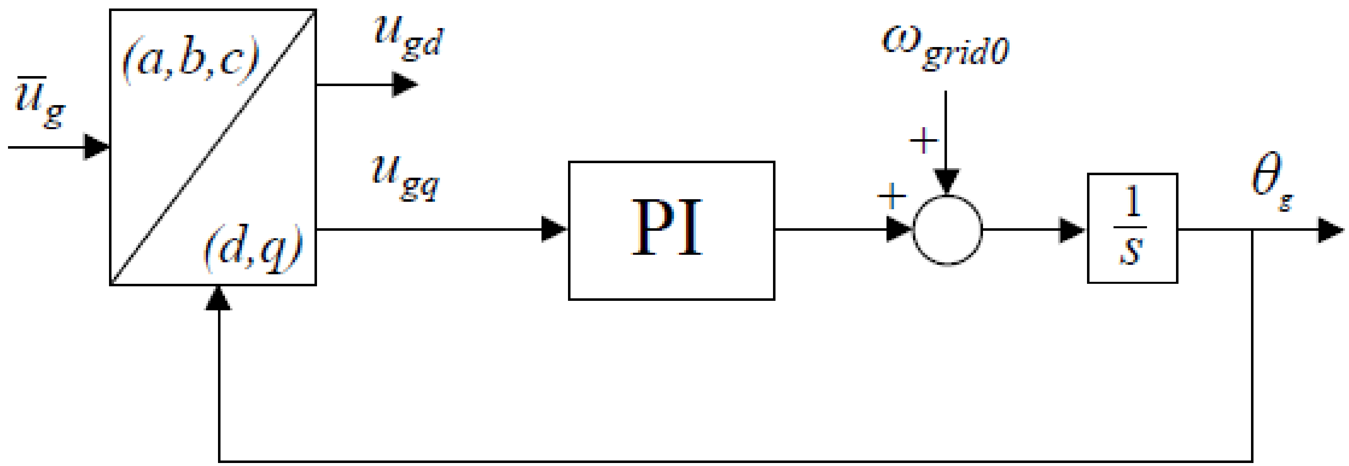
Upravljanje mrežnim pretvaračem

Active and reactive power



Grid synchronisation

- Phased-locked loop (PLL)



Grid currents control

- Voltage oriented control

$$u_{d\_PWM} = R_{gf} i_{gd} + L_{gf} \frac{di_{gd}}{dt} + \omega_{gf} L_{gf} i_{gq} + u_{gd}$$

$$u_{q\_PWM} = R_{gf} i_{gq} + L_{gf} \frac{di_{gq}}{dt} - \omega_{gf} L_{gf} i_{gd} + u_{gq}$$

- Decoupling

$$u_{d\_PWM} + \Delta u_{gd} = R_{gf} i_{gd} + L_{gf} \frac{di_{gd}}{dt}$$

$$u_{q\_PWM} + \Delta u_{gq} = R_{gf} i_{gq} + L_{gf} \frac{di_{gq}}{dt}$$

Grid currents control

- PWM mathematical model

$$G_{PWM} = \frac{1}{1 + s1.5T_s}$$

- PI current controllers:

$$T_{Id,q} = \frac{L_{gf}}{R_{gf}}, \qquad K_{rd,q} = \frac{L_{gf}}{3R_s}$$

- Closed loop transfer function:F

$$\frac{i_{gd}(s)}{i_{gd}^*(s)} = \frac{i_{gq}(s)}{i_{gq}^*(s)} = \frac{1}{1 + s3T_s}$$

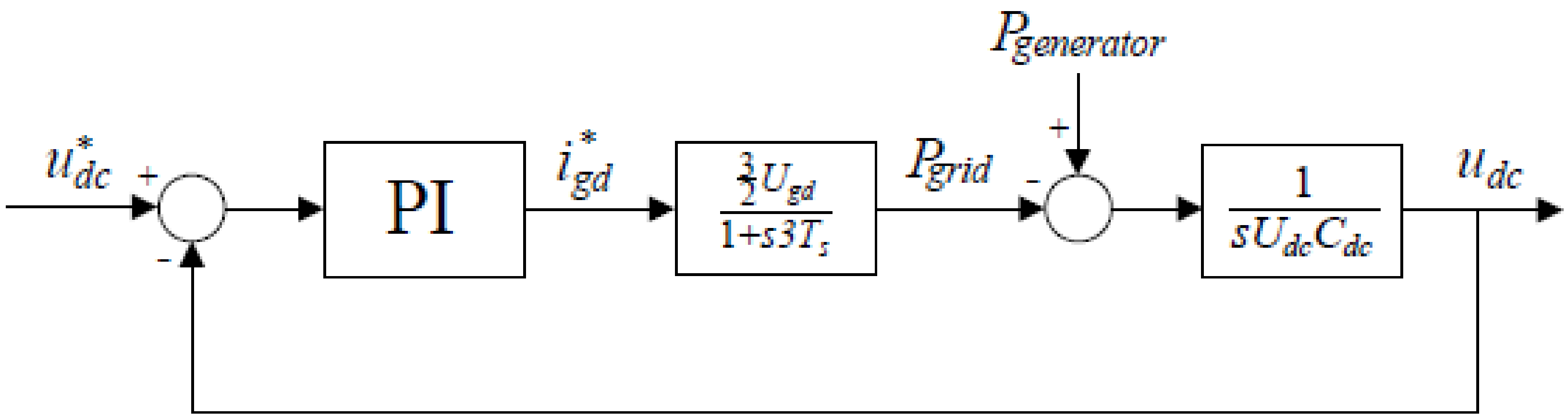
DC-link control

- DC-link mathematical model

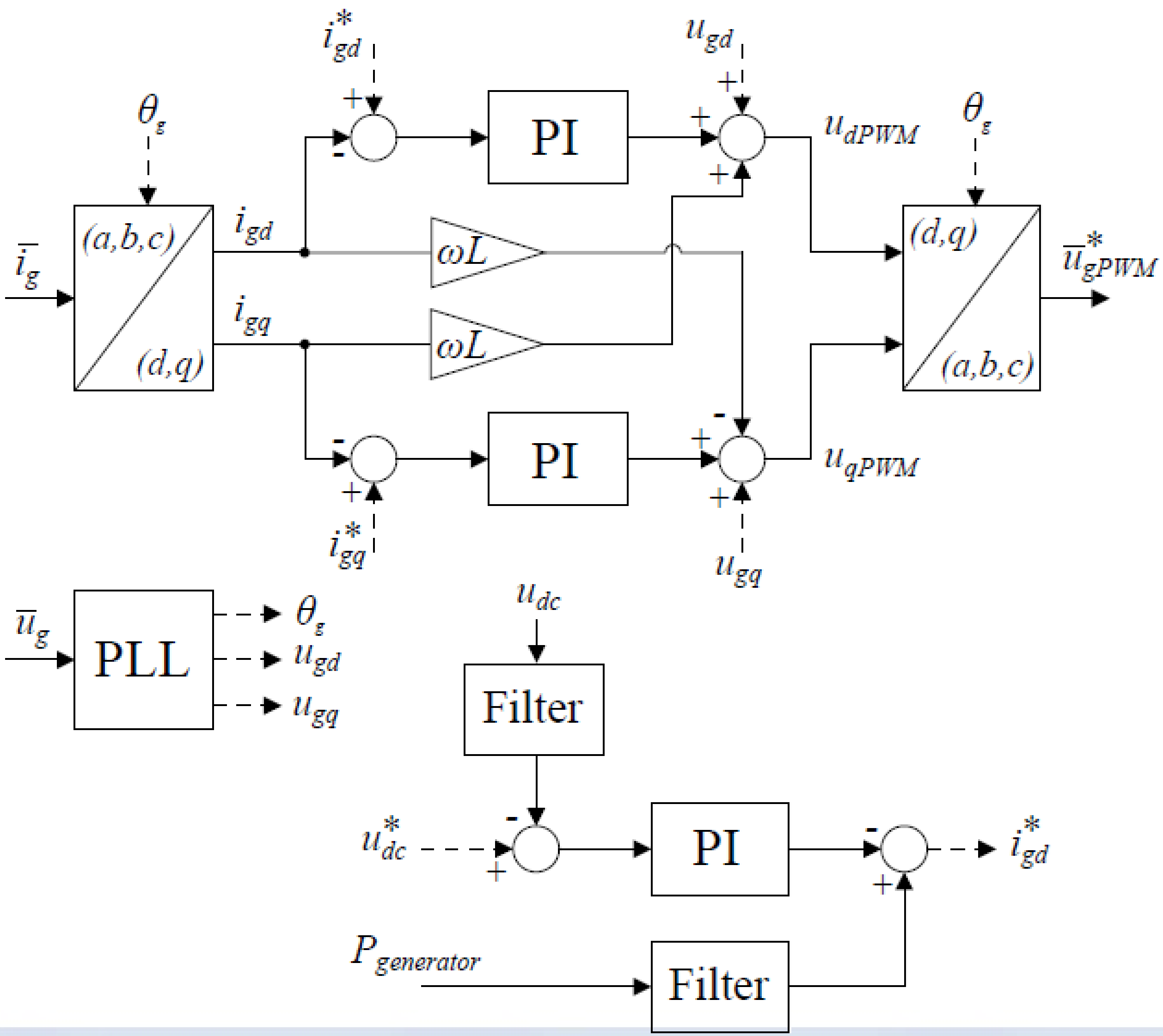
$$\frac{\Delta u_{dc}}{\Delta P_{grid}} = -\frac{1}{sU_{dc}C_{dc}}$$

- PI controller

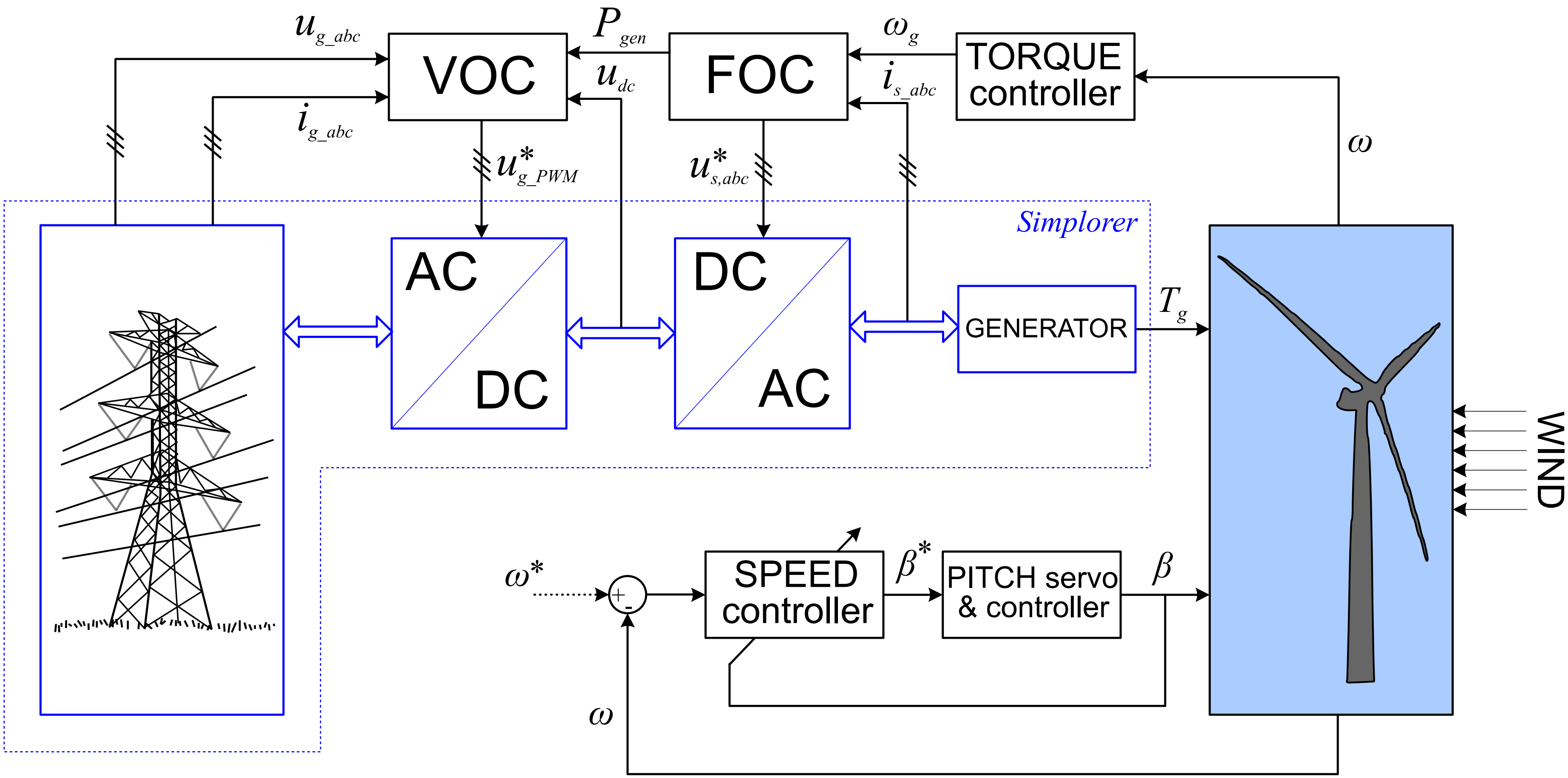
$$T_{Idc} = 12T_s, \quad K_{rdc} = \frac{U_{dc}C_{dc}}{9U_{gd}T_s}$$



Voltage-oriented control



Wind turbine control



Zaključak

- FOC rely on well-determined flux position → Kalman filter observers
- PI controllers widely spread, main researches are directed to model predictive control and speed sensorless control
- VOC rely on well-synchronized grid voltage → Phase-locked loop algorithms
- UKF is robust, needs less effort for internal parameter tuning, can be extended for parameter estimation

Zahvala

Projekte **CEEStructHealth** i **Will4Wind** sufinancira Europska unija kroz Europski fond za regionalni razvoj.

Dodatne informacije: http://act.rasip.fer.hr/

LARES Laboratorij za sustave obnovljivih izvora energije
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Projekt je sufinancirala Europska unija iz Europskog fonda za regionalni razvoj

Hvala na pažnji!

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