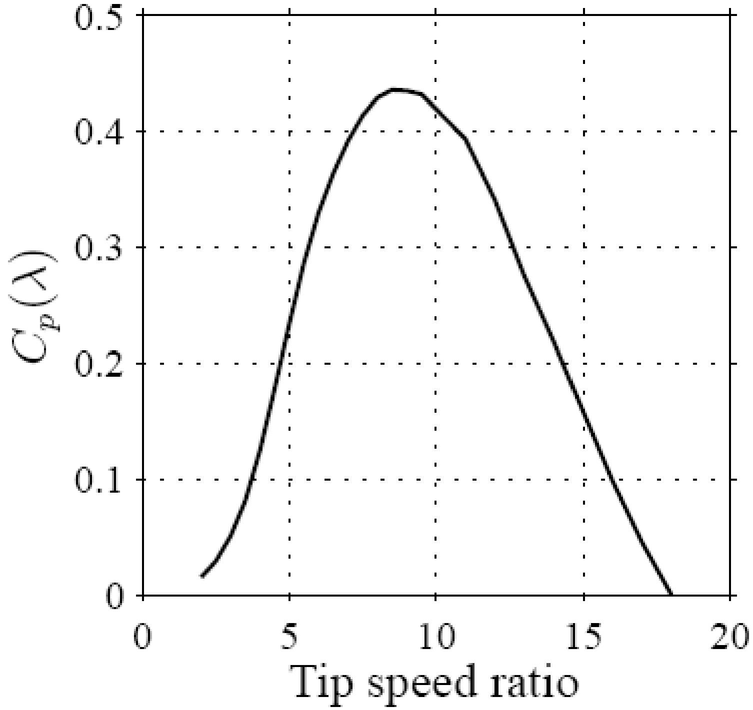
ECE 802, Electric Motor Control

Dual-Fed Induction Generators for Wind Power

Power Coefficient

$C_p(\lambda,\beta)$ - ratio of power from a wind turbine to the power available in the wind



β - pitch angle (rad)
λ - tip speed ratio

$$\lambda = \frac{\omega_{rmt} R}{v_w}$$

ω_{rmt} - speed of the wind turbine (rad/s)
R - radius of the wind turbine (m)
v_w - wind velocity (m/s)

Betz limit: $C_p \leq 59.3\%$

A. Petersson, Analysis, *Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines*, Ph.D. Dissertation, Chalmers University of Technology, Sweden, 2005.

Example Wind Turbine

Wind turbine		Induction generator		Power network	
Rated capacity	3.6 MW	P_{rated}	3.6 MW	r_{l1}	0.14
Cut-in wind speed	3.5 m/s	$V_{\text{s,rated}}$	4.16 kV	x_{l1}	0.8
Cut-out wind speed	27 m/s	r_s	0.0079	r_{l2}	0.14
Rated wind speed	14 m/s	r_r	0.025	x_{l2}	0.8
Number of blades	3	L_{ls}	0.07939	Z_L	$0.7+j1.5$
Rotor diameter	104 m	L_{lr}	0.40		
Swept area	8495 m^2	L_m	4.4		
Rotor speed	8.5-15.3 rpm	pf	-0.9 ~ +0.9		

$$\mathrm{RPM} := \frac{2\cdot\pi\cdot \mathrm{rad}}{\mathrm{min}}$$

$$R := \frac{104\cdot \mathrm{m}}{2}$$

$$\omega_{rmt\_min} := 8.5\cdot \mathrm{RPM}$$

$$\omega_{rmt\_max} := 15.3\cdot \mathrm{RPM}$$

$$v_{w\_min} := 3.5\cdot\frac{\mathrm{m}}{\mathrm{s}}$$

$$v_{w\_max} := 27\cdot\frac{\mathrm{m}}{\mathrm{s}}$$

$$\lambda_{min} := \frac{\omega_{rmt\_min}\cdot R}{v_{w\_max}}$$

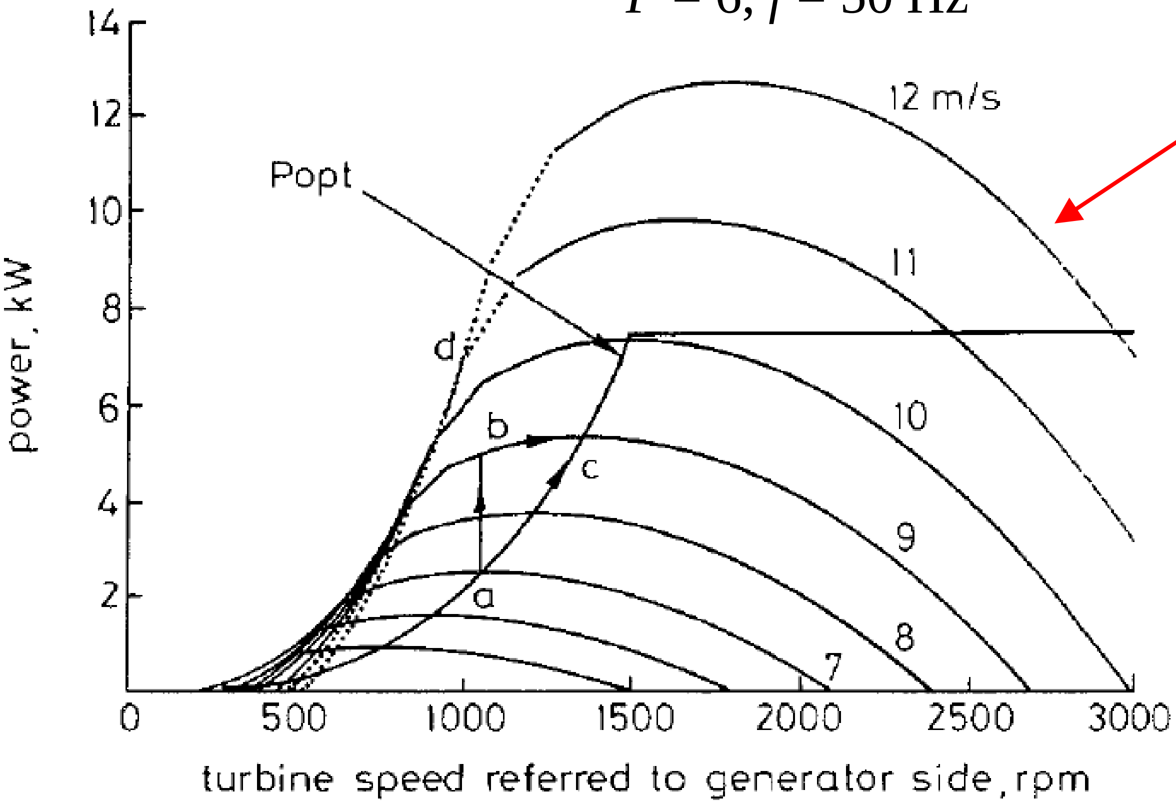
$$\lambda_{max} := \frac{\omega_{rmt\_max}\cdot R}{v_{w\_min}}$$

W. Qiao, G.K. Venayagamoorthy, and R.G. Harley, "Real-Time Implementation of a STATCOM on a Wind Farm Equipped With Doubly Fed Induction Generators," *IEEE Transactions on Industry Applications*, volume 45, number 1, pages 98-107, January/February 2009.

Power Versus Rotational Speed

constant pitch angle β

$P = 6, f = 50\ \text{Hz}$



$$P_m = \frac{1}{2} C_p(\lambda, \beta)\pi \rho R^2 v_w^3$$

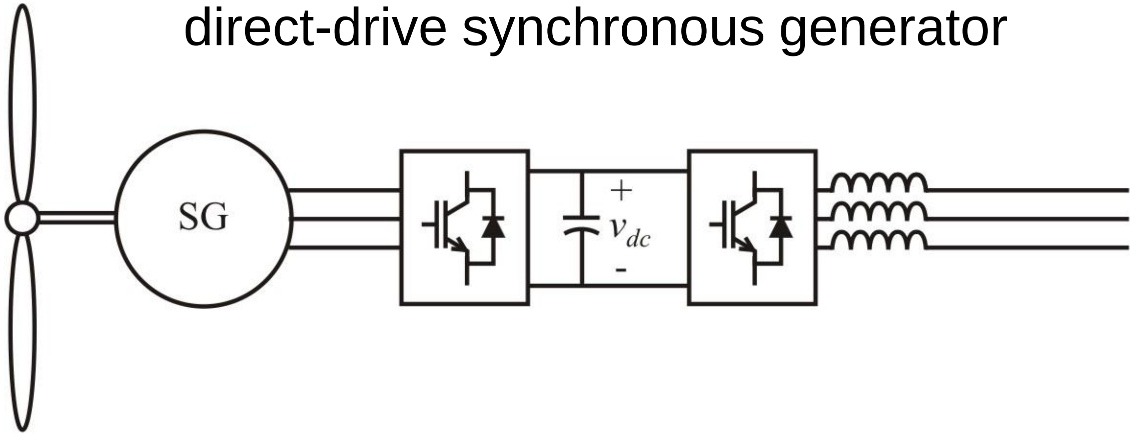
$$P_{opt} = K_{opt}\omega_{rm}^2$$

- command P_{opt} from the wind turbine drive
- limit command to rated power
- above rated speed, use pitch angle to regulate speed

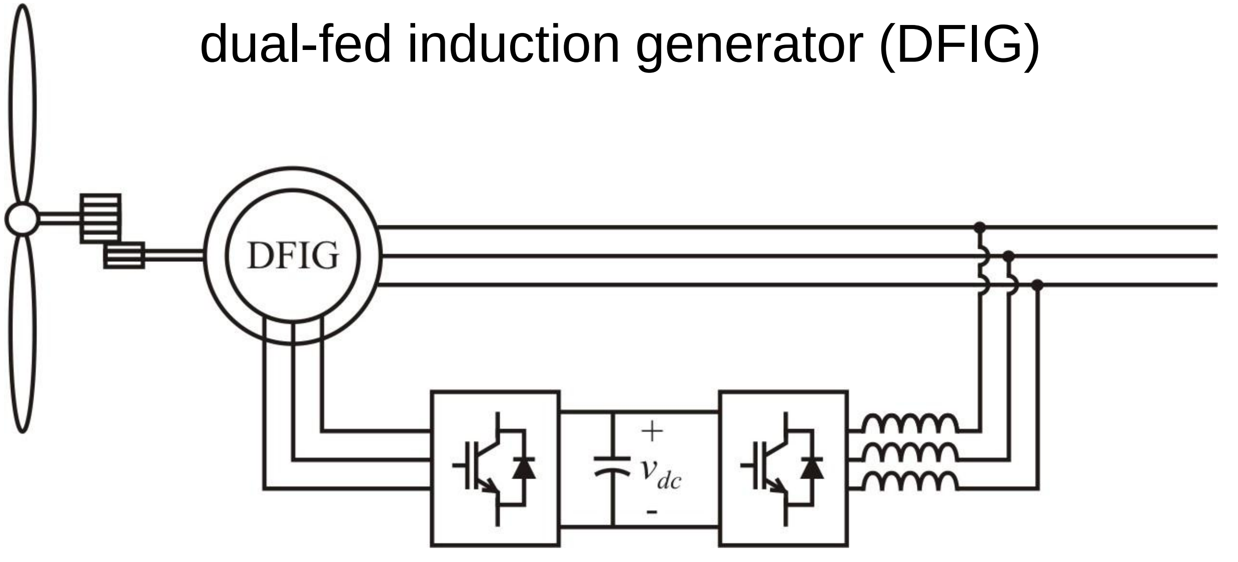
R. Pena, J.C. Clare, and G.M Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," *IEE Proceedings - Electric Power Applications*, volume 143, Issue 3, pages 231-241, May 1996.

Wind Power System Diagrams

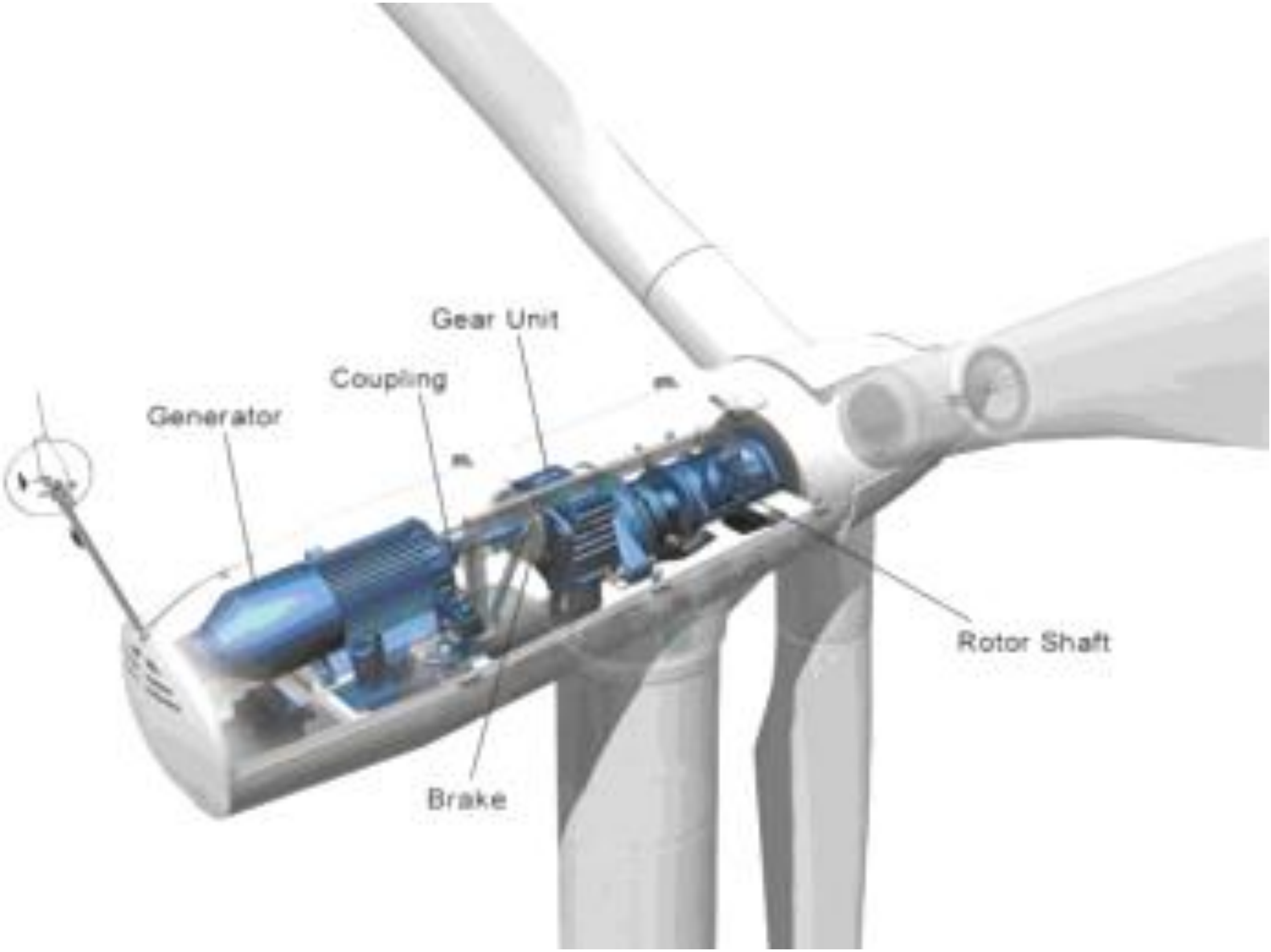
direct-drive synchronous generator



dual-fed induction generator (DFIG)



Wind Turbine Diagram



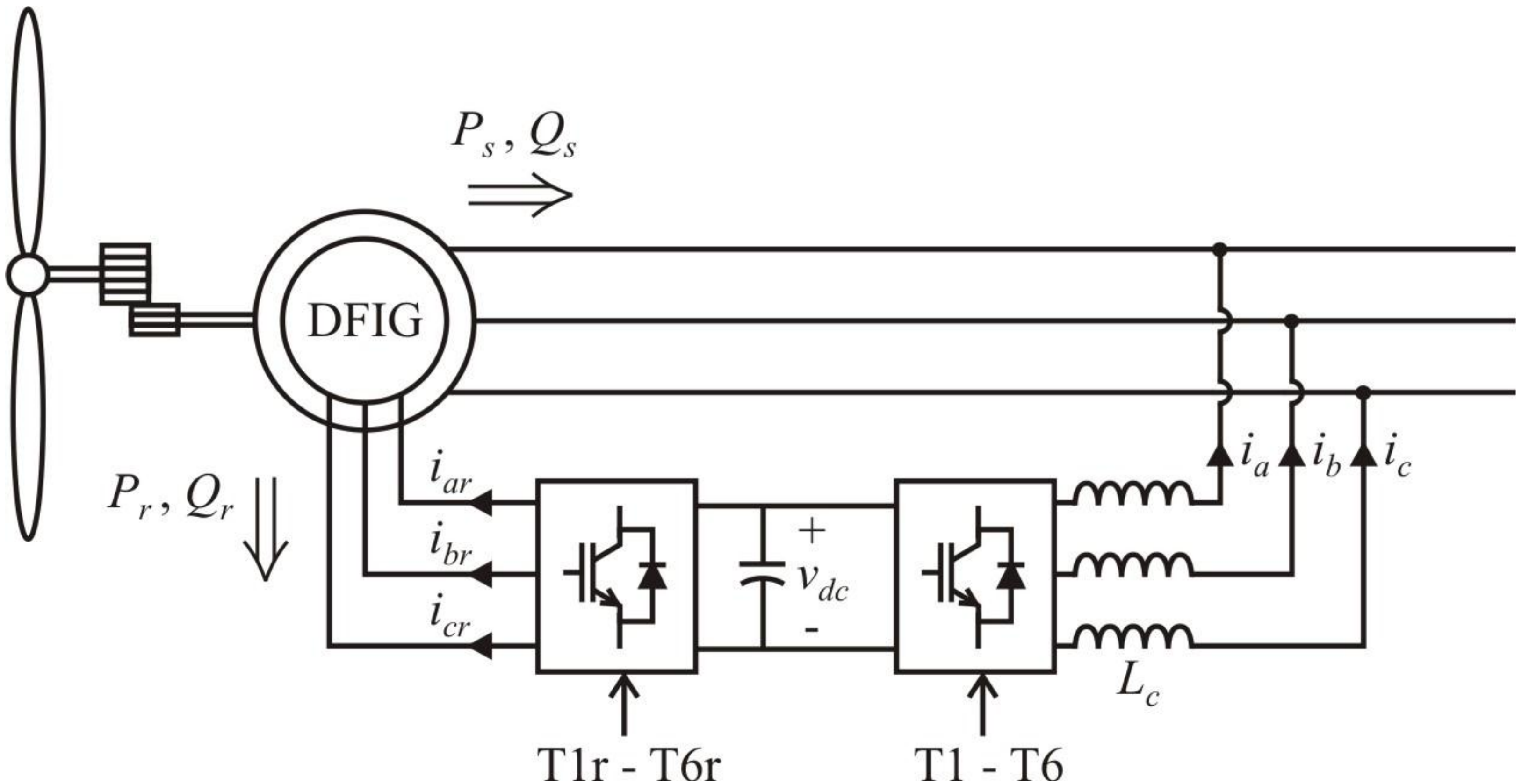
Wind Power Basics

Amount of energy harvested from the wind is express as a power coefficient which depends on the tip speed ratio and blade pitch angle

According to theory, the power coefficient is limited to 59.3%

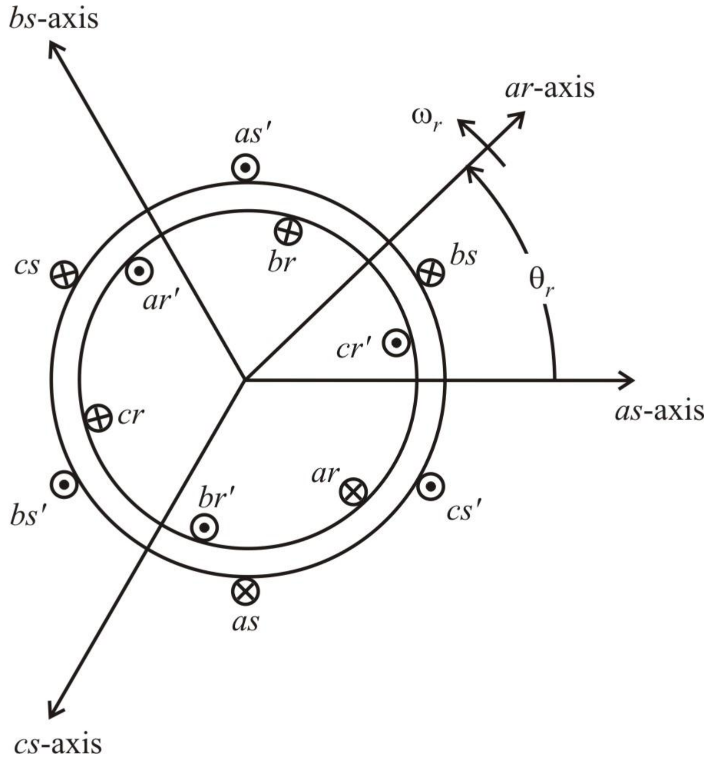
Given the specific power coefficient curves for a particular wind turbine, the commanded power from the turbine drive can be set to the maximum power available for a given wind speed

DFIG System



dual fed induction generator (DFIG)
or wound-rotor induction machine (WRIM)

Symmetrical Induction Machines (Chapter 4)



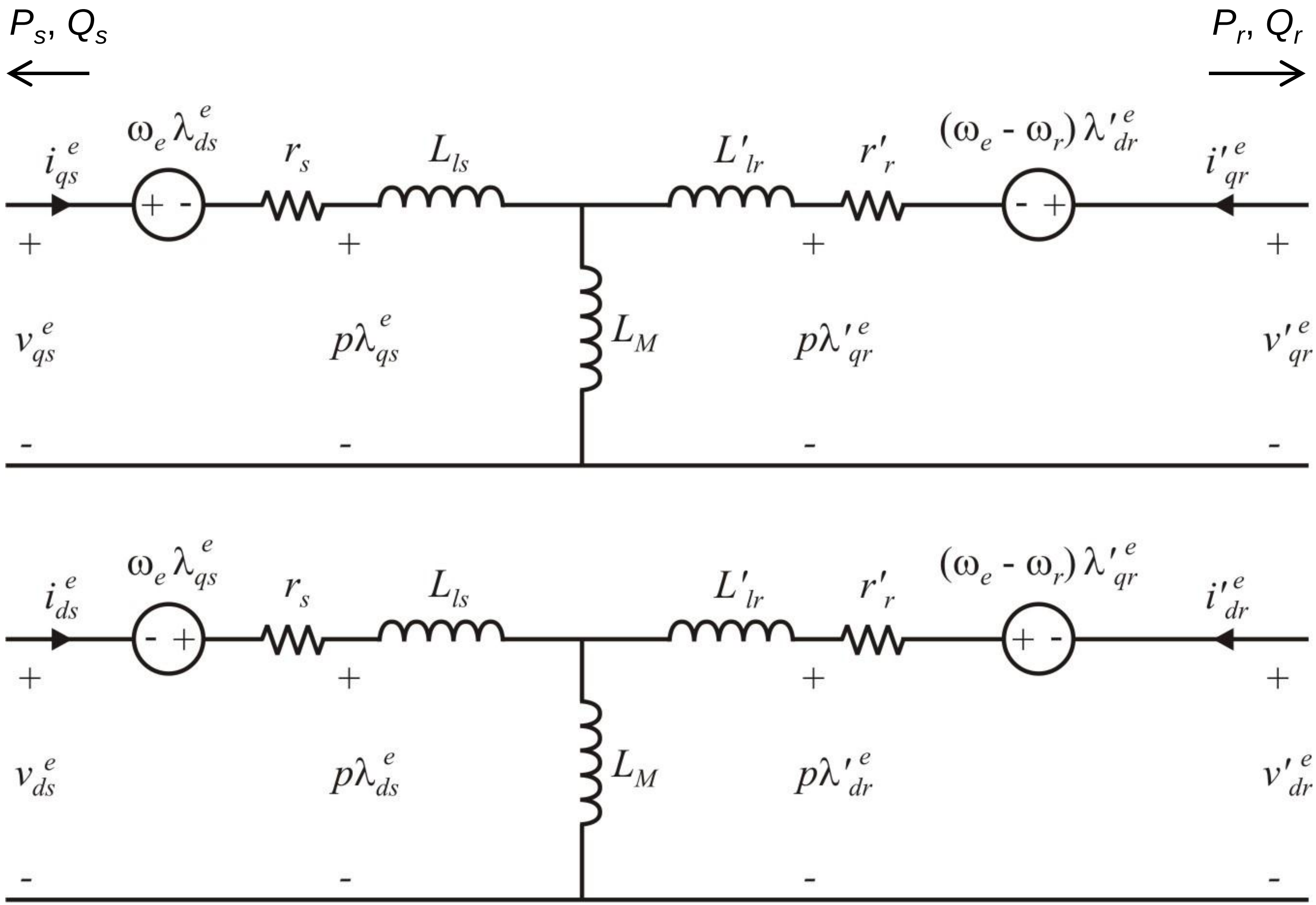
voltage equations

$$v_{abcs} = r_s i_{abcs} + p\lambda_{abcs}$$

$$v_{abcr} = r_r i_{abcr} + p\lambda_{abcr}$$

typically wye connected windings

IM *q-d* Equivalent Circuit (Synchronous Reference Frame)



IM Stator Side Equations

steady-state, synchronous reference frame

$$V_{qs}^{e} = r_s I_{qs}^{e} + \omega_e \lambda_{ds}^{e} \qquad \lambda_{qs}^{e} = L_{ss} I_{qs}^{e} + L'_{lr} I'^{e}_{qr}$$

$$V_{ds}^{e} = r_s I_{ds}^{e} - \omega_e \lambda_{qs}^{e} \qquad \lambda_{ds}^{e} = L_{ss} I_{ds}^{e} + L'_{lr} I'^{e}_{dr}$$

substitute flux linkage equations into voltage equations

$$V_{qs}^{e} = r_s I_{qs}^{e} + \omega_e L_{ss} I_{ds}^{e} + \omega_e L'_{lr} I'^{e}_{dr}$$

$$V_{ds}^{e} = r_s I_{ds}^{e} - \omega_e L_{ss} I_{qs}^{e} - \omega_e L'_{lr} I'^{e}_{qr}$$

solve for stator currents

$$\begin{bmatrix} I_{qs}^{e} \\ I_{ds}^{e} \end{bmatrix} = \begin{bmatrix} r_s & \omega_e L_{ss} \\ -\omega_e L_{ss} & r_s \end{bmatrix}^{-1} \begin{bmatrix} V_{qs}^{e} - \omega_e L_M I'^{e}_{dr} \\ V_{ds}^{e} + \omega_e L_M I'^{e}_{qr} \end{bmatrix}$$

Stator Currents in Terms of Rotor Currents

in the synchronous reference frame $V_{qs}^{e} = \sqrt{2}\,V_{s}$ $V_{ds}^{e} = 0$

assuming that $\omega_e L_{ss} >> r_s$

Stator Side Power

stator power

$$P_s = -\frac{3}{2}\left(V_{qs}^e I_{qs}^e + V_{ds}^e I_{ds}^e\right) = -\frac{3}{2}\sqrt{2}V_s I_{qs}^e$$

$$Q_s = -\frac{3}{2}\left(V_{qs}^e I_{ds}^e - V_{ds}^e I_{qs}^e\right) = -\frac{3}{2}\sqrt{2}V_s I_{ds}^e$$

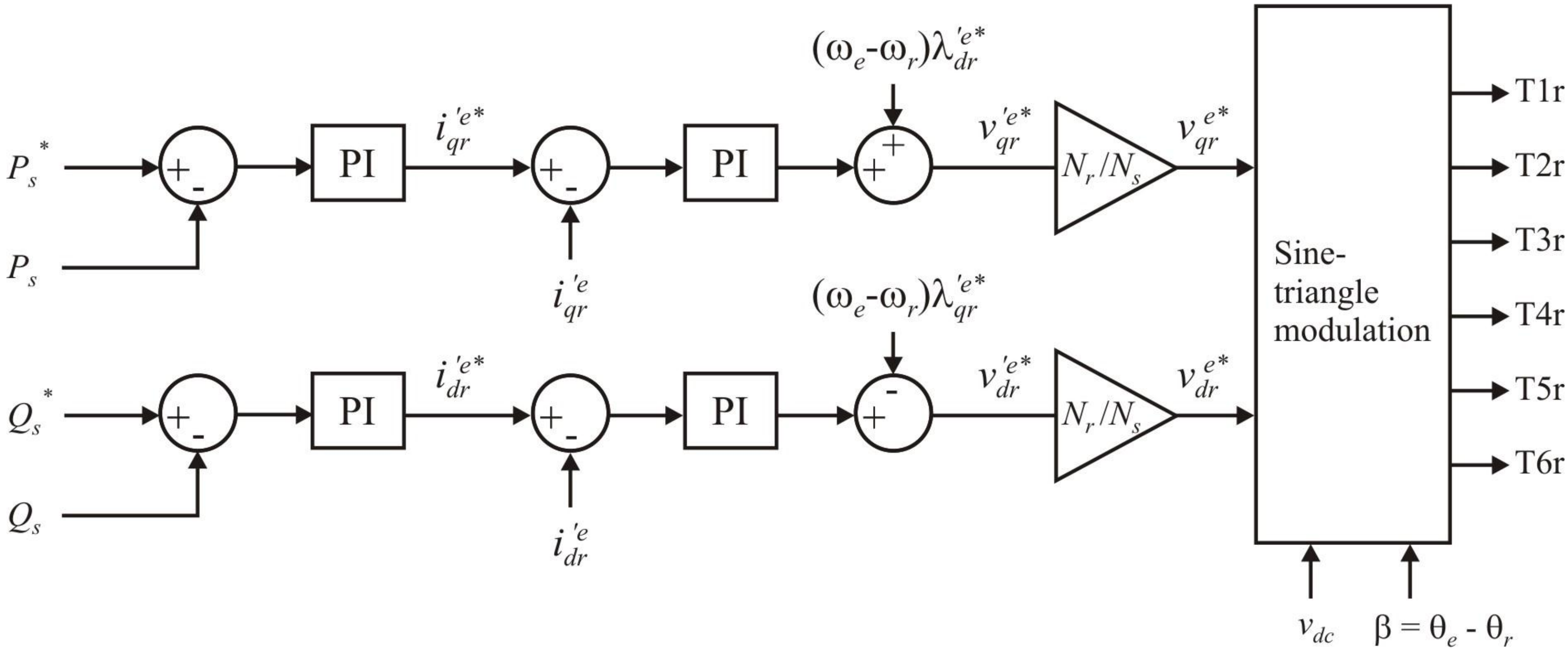
in terms of rotor currents

$$P_s \approx \frac{3}{2}\frac{\sqrt{2}V_s L_M}{L_{ss}} I'^e_{qr}$$

$$Q_s \approx \frac{3}{2}\frac{\sqrt{2}V_s L_M}{L_{ss}} I'^e_{dr} - \frac{3V_s^2}{\omega_e L_{ss}}$$

Note: stator real power can be controlled by *q*-axis rotor current in the synchronous reference frame. Stator reactive power is controlled by *d*-axis rotor current.

IM Rotor Side Converter (RSC) Control



Flux Linkage Calculations

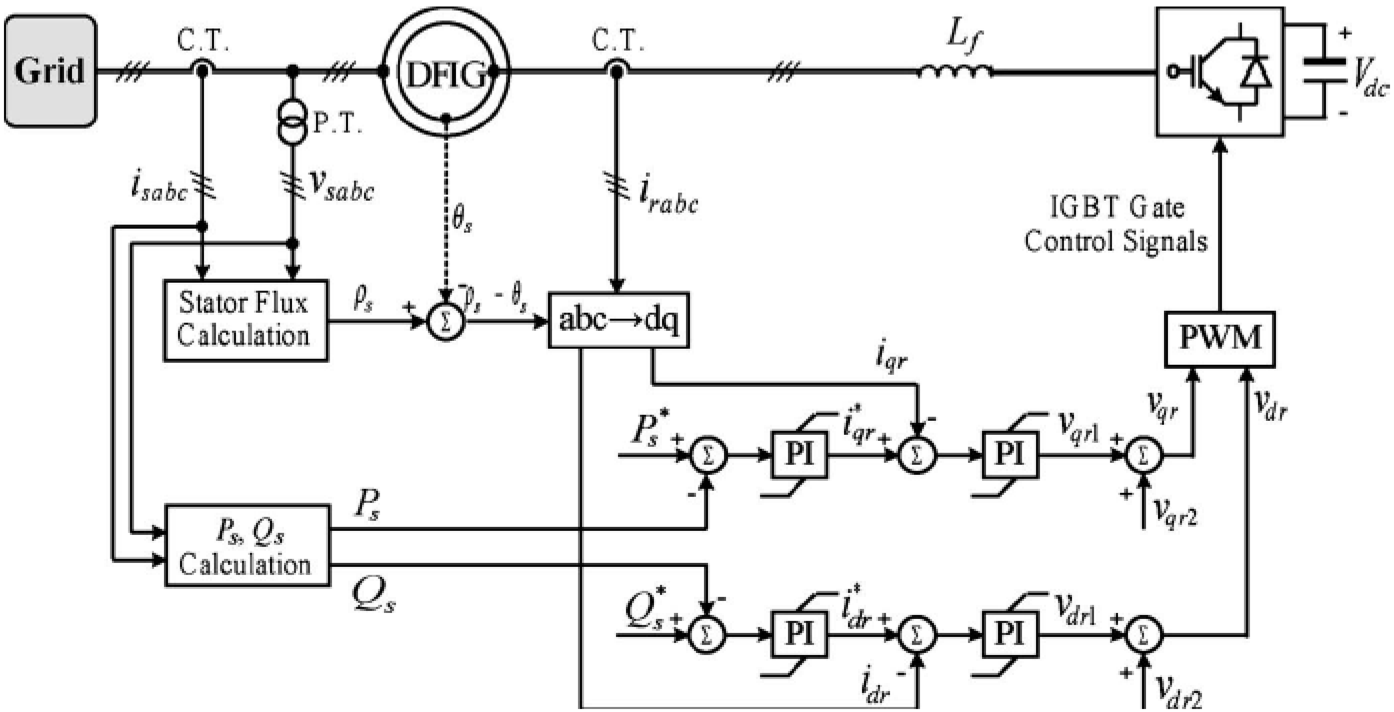
$$\lambda'^{e*}_{qr} = L'_{rr} i'^{e*}_{qr} + L_M i^{e*}_{qs}$$

$$\lambda'^{e*}_{dr} = L'_{rr} i'^{e*}_{dr} + L_M i^{e*}_{ds}$$

$$i^{e*}_{qs} = -\frac{L_M}{L_{ss}} i'^{e*}_{qr}$$

$$i^{e*}_{ds} = \frac{\sqrt{2} V_s}{\omega_e L_{ss}} - \frac{L_M}{L_{ss}} i'^{e*}_{dr}$$

IM Rotor Converter Control



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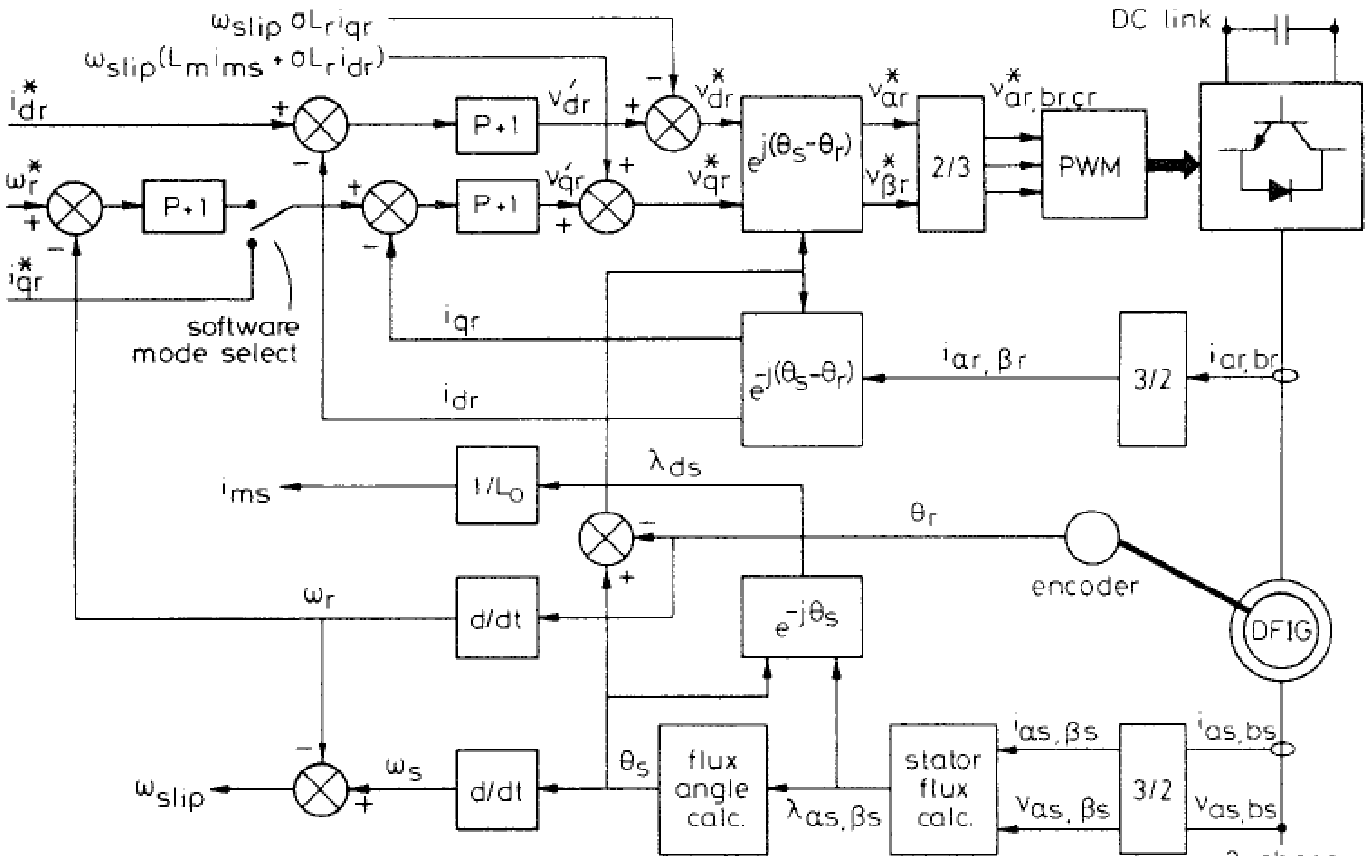
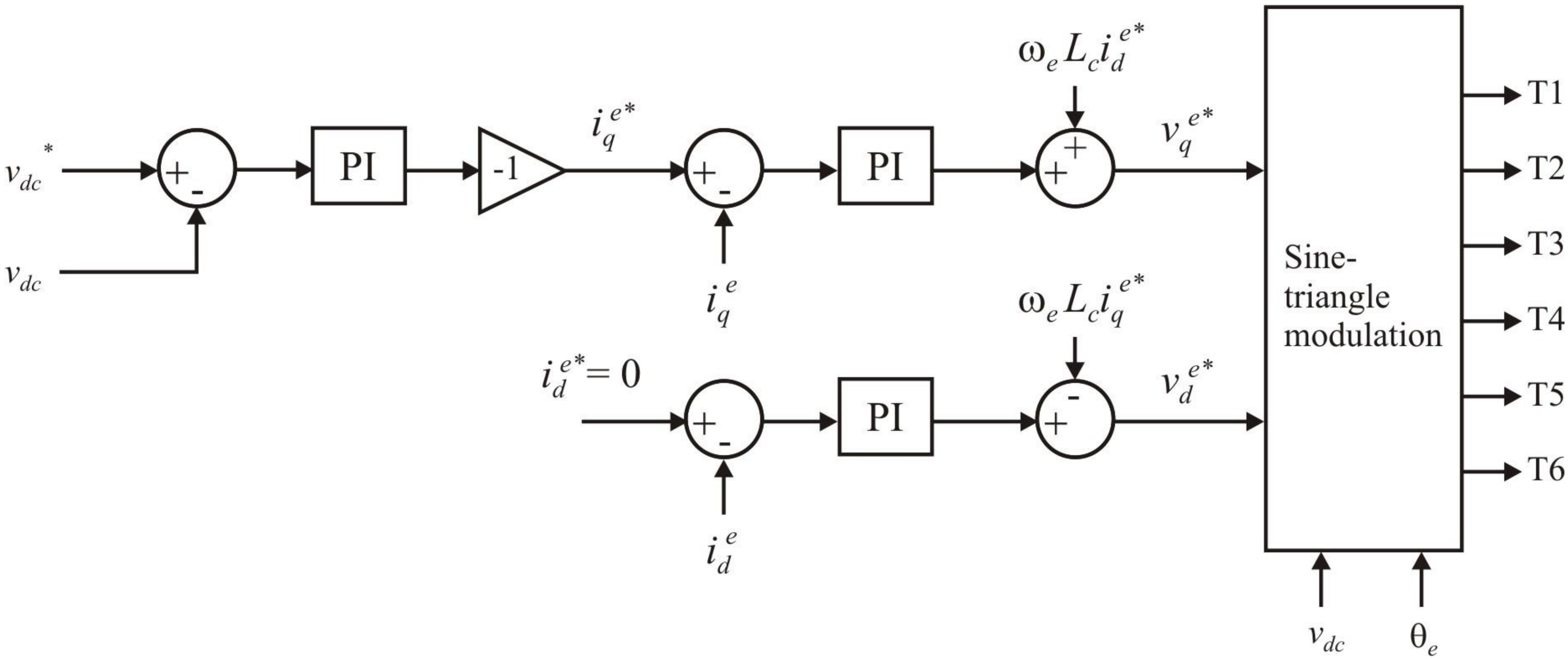
IM Rotor Converter Control



Vector-control structure for DFIG

R. Pena, J.C. Clare, and G.M Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," *IEE Proceedings - Electric Power Applications*, volume 143, Issue 3, pages 231-241, May 1996.

Grid Side Converter (GSC) Control



- reactive power can also be controlled through the *d*-axis current

Example using 2250hp Machine from Book

WRIM induction machine

$r_s := 0.029\cdot\Omega$ $\quad P := 4$ $\quad r'_r := 0.022\cdot\Omega$

$L_{ls} := 600\cdot\mu H$ $\quad L_M := 34.6\cdot mH$ $\quad L'_{lr} := 600\cdot\mu H$

$\omega_e := 2\cdot\pi\cdot 60\cdot Hz$

$$V_s := \frac{2300\cdot V}{\sqrt{3}}$$

$L_{ss} := L_{ls} + L_M$

$L'_{rr} := L'_{lr} + L_M$

commanded stator power and rotor currents

$P_{s\_star} := 1.6\cdot MW$ $\quad Q_{s\_star} := 0\cdot MVAR$

$$I'_{qre} := \frac{2}{3}\cdot\frac{L_{ss}}{\sqrt{2}\cdot V_s\cdot L_M}\cdot P_{s\_star}$$

$$I'_{dre} := \frac{2}{3}\cdot\frac{L_{ss}}{L_M}\cdot\frac{Q_{s\_star}}{\sqrt{2}\cdot V_s} + \frac{\sqrt{2}\cdot V_s}{\omega_e\cdot L_M}$$

actual stator power

$$V_{qse} := \sqrt{2}\cdot V_s$$

$$V_{dse} := 0\cdot V$$

$$\begin{pmatrix} I_{qse} \\ I_{dse} \end{pmatrix} := \begin{pmatrix} r_s & \omega_e\cdot L_{ss} \\ -\omega_e\cdot L_{ss} & r_s \end{pmatrix}^{-1} \cdot \begin{pmatrix} \sqrt{2}\cdot V_s - \omega_e\cdot L_M\cdot I'_{dre} \\ \omega_e\cdot L_M\cdot I'_{qre} \end{pmatrix}$$

$$P_s := -\frac{3}{2}\cdot\left(V_{qse}\cdot I_{qse} + V_{dse}\cdot I_{dse}\right)$$

$$Q_s := -\frac{3}{2}\cdot\left(V_{qse}\cdot I_{dse} - V_{dse}\cdot I_{qse}\right)$$

rotor power as a funciton of speed

$$\lambda'_{qre} := L'_{rr} \cdot I'_{qre} + L_M \cdot I_{qse}$$

$$\lambda'_{dre} := L'_{rr} \cdot I'_{dre} + L_M \cdot I_{dse}$$

$$V'_{qre}(\omega_r) := r'_r \cdot I'_{qre} + (\omega_e - \omega_r) \cdot \lambda'_{dre}$$

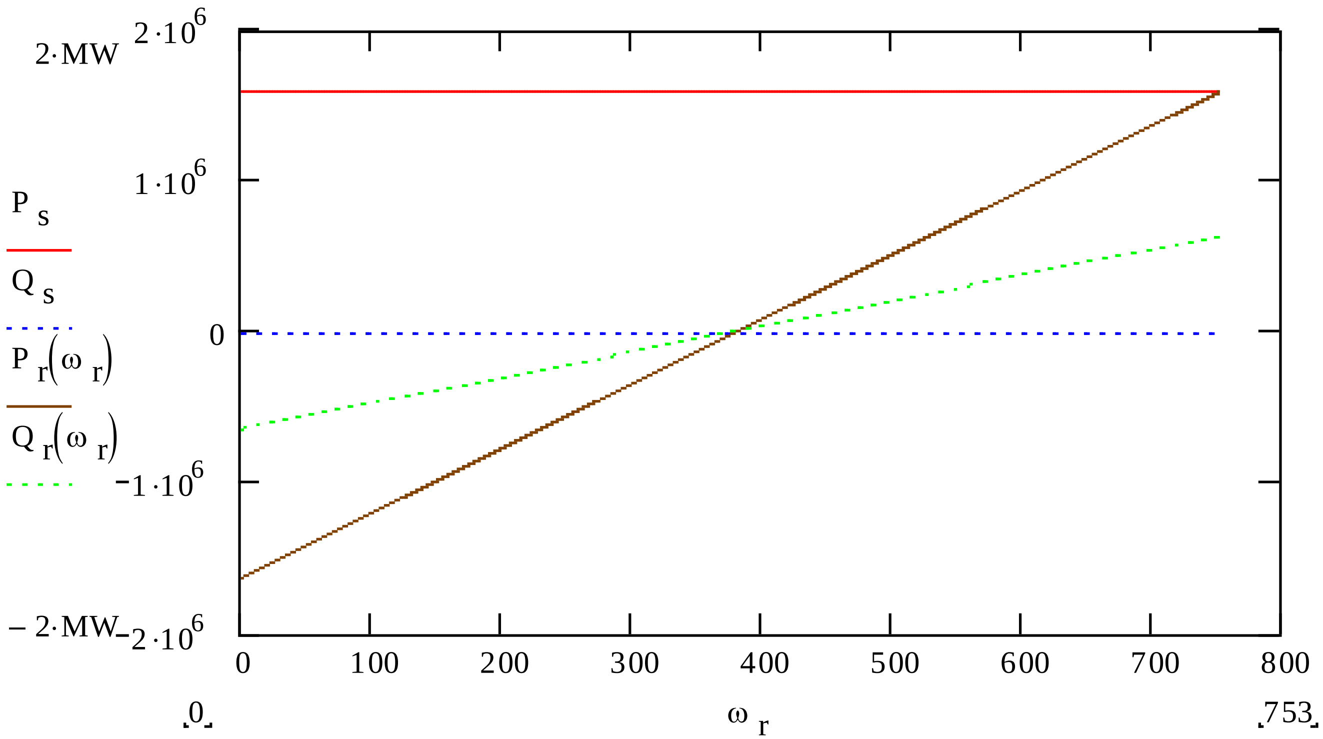
$$V'_{dre}(\omega_r) := r'_r \cdot I'_{dre} - (\omega_e - \omega_r) \cdot \lambda'_{qre}$$

$$P_r(\omega_r) := -\frac{3}{2} \cdot \left(V'_{qre}(\omega_r) \cdot I'_{qre} + V'_{dre}(\omega_r) \cdot I'_{dre}\right)$$

$$Q_r(\omega_r) := -\frac{3}{2} \cdot \left(V'_{qre}(\omega_r) \cdot I'_{dre} - V'_{dre}(\omega_r) \cdot I'_{qre}\right)$$

$$\omega_r := 0 \cdot \frac{rad}{s}, 1 \cdot \frac{rad}{s} .. 2 \cdot \omega_e$$

Stator and Rotor Power Versus Speed



rotor speed range based on rotor power constraints

$$P_{r\_min} := -0.3 \cdot |P_s|$$

$$P_{r\_max} := 0.3 \cdot |P_s|$$

$$\omega_{guess} := \omega_e$$

$$\omega_{r\_min} := \mathrm{root}\left[\left(P_r\left(\omega_{guess}\right) - P_{r\_min}\right), \omega_{guess}\right]$$

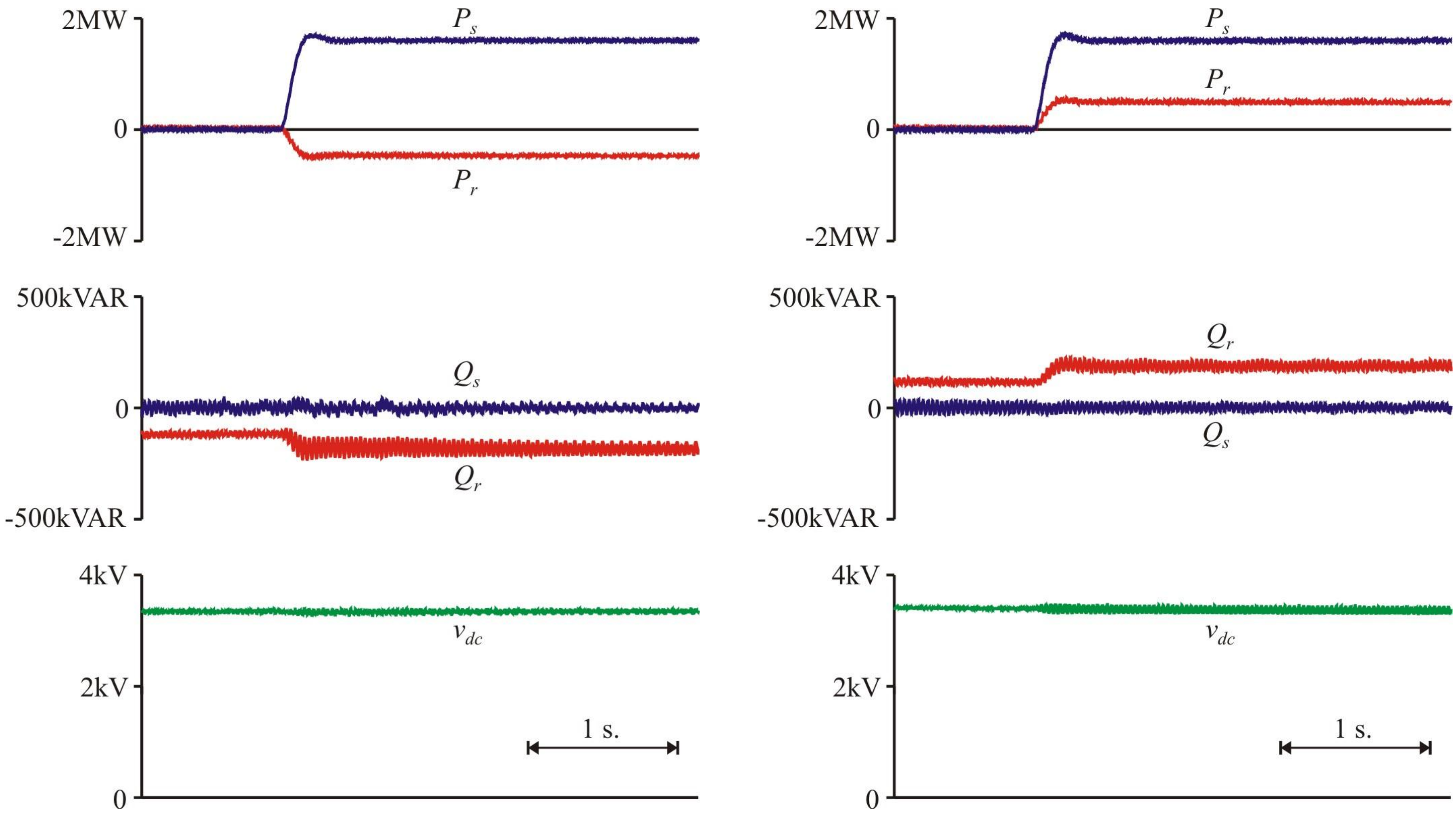
$$\omega_{r\_max} := \mathrm{root}\left[\left(P_r\left(\omega_{guess}\right) - P_{r\_max}\right), \omega_{guess}\right]$$

$$\omega_{rm\_min} := \frac{2}{P} \cdot \omega_{r\_min}$$

$$\omega_{rm\_max} := \frac{2}{P} \cdot \omega_{r\_max}$$

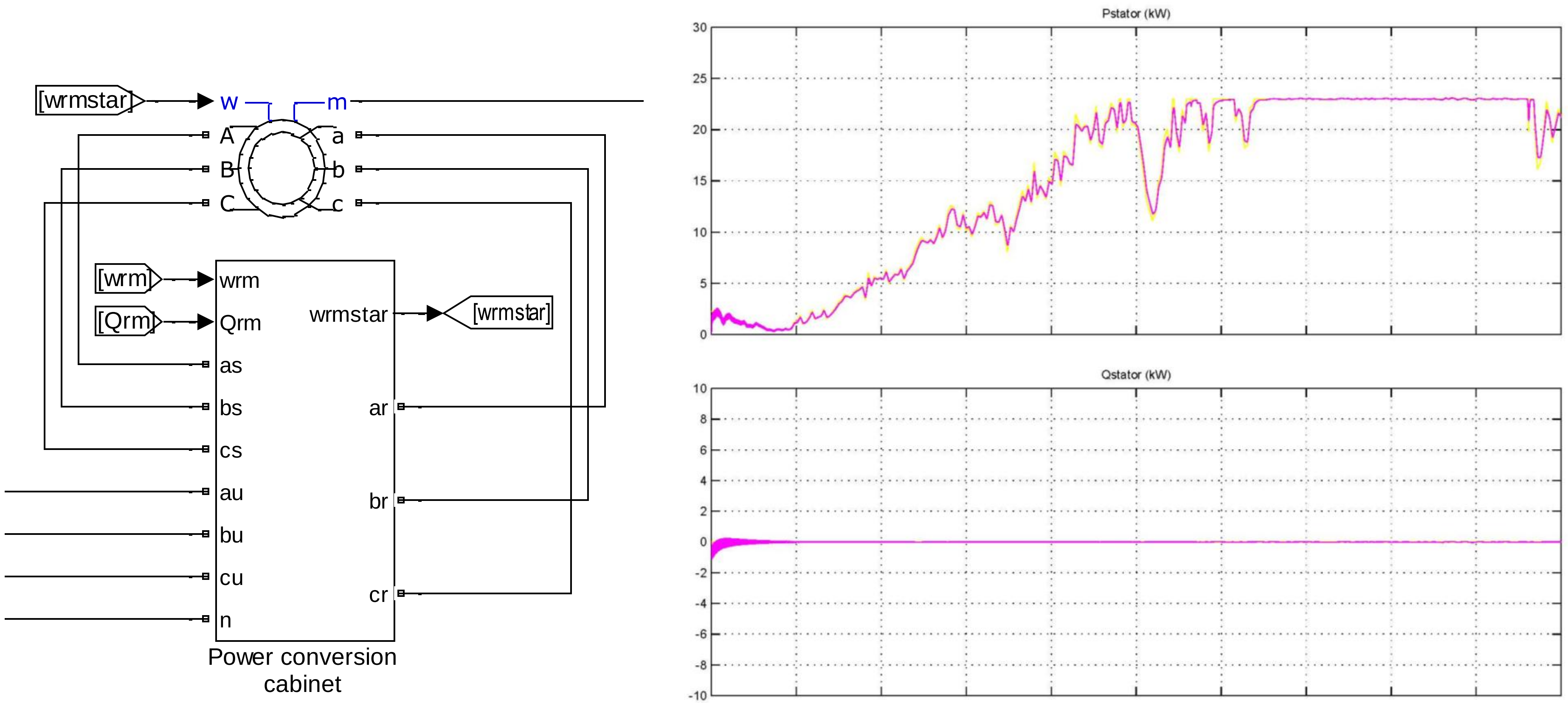
Simulated DFIG with Step in Commanded Power

L_c = 500 µH, v_{dc}* = 3700 V



ω_{rm} = 1278 r/min ω_{rm} = 2348 r/min

Example 30kW Machine with Wind Data



DFIG for Wind Power Applications

Stator real and reactive power can be controlled using the synchronous reference frame *q*- and *d*-axis rotor currents respectively

Grid side converter used to regulate the capacitor voltage

Typically the rotor power converter size is limited which leads to a practical limit on the speed range