University of Strathclyde Engineering

Modelling and Control of Wind Generation Systems

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TUTORIAL:
Transmission and Integration of Wind Power Systems:
Issues and Solutions
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INSTITUTE FOR ENERGY AND ENVIRONMENT

Programme

1. Introduction
2. Wind turbine technologies
3. Optimum power extraction from wind
4. Dynamic model of the Doubly-Fed Induction Generator (DFIG)
5. Control of DFIG-based wind turbines
    5.1. Provision of synchronising torque characteristic
    5.2. Short-term frequency control
    5.3. Provision of Power System Stabiliser (PSS)
6. Impact of wind farms on transient and dynamic stability
7. PSS for a generic DFIG controller
8. References

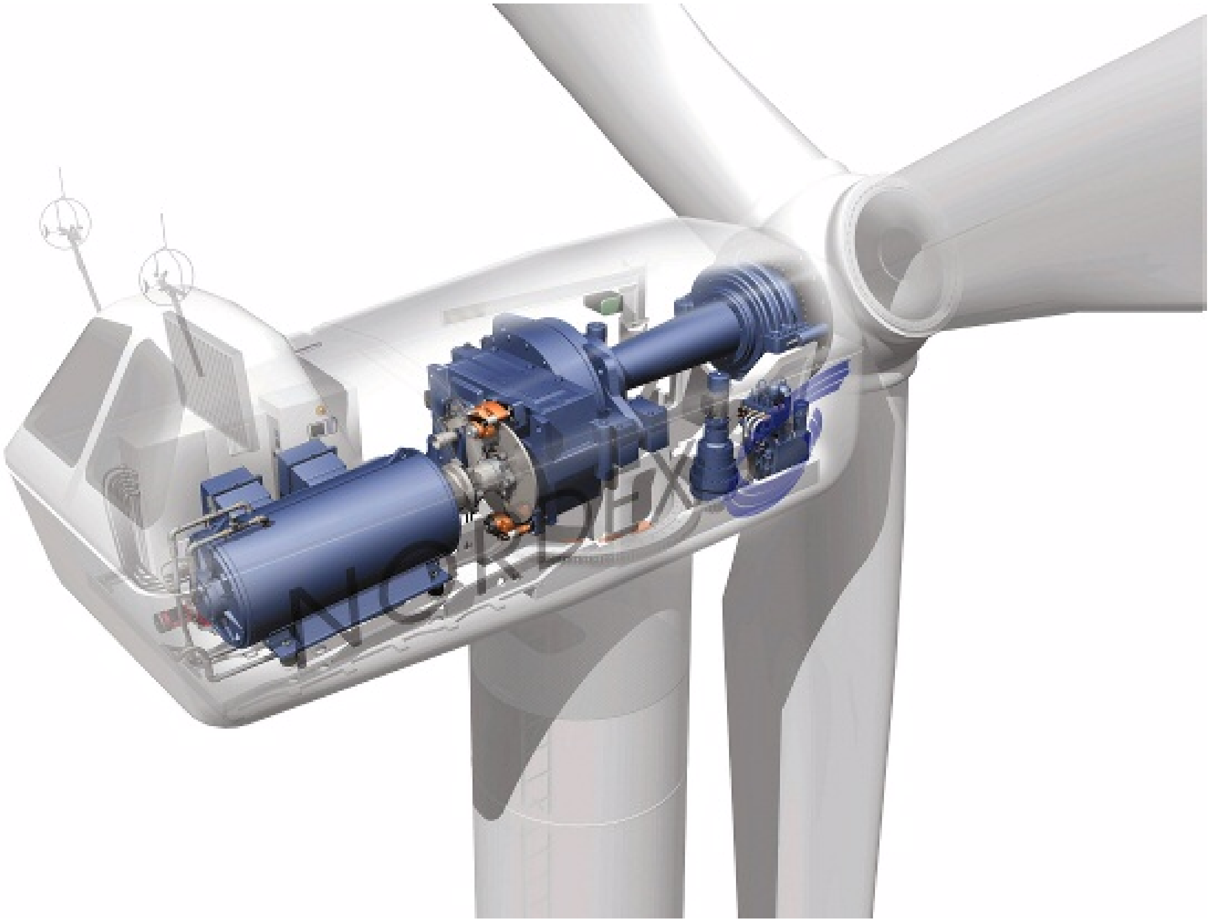
1. Introduction

Introduction

- Wind power is presently the most cost-effective renewable technology and provides a continuously growing contribution to climate change goals, energy diversity and security.
- Integration of large amounts of wind power into electricity networks face however various strong challenges:
  - Technical characteristics of wind turbine technologies are different from conventional power plants.
  - Wind intermittency
  - Grid availability and reliability
  - Grid Code compliance

Accurate modelling and control of wind turbine systems for power system studies are required to help solving these challenges

Wind turbine components



Source: www.nordex-online.com

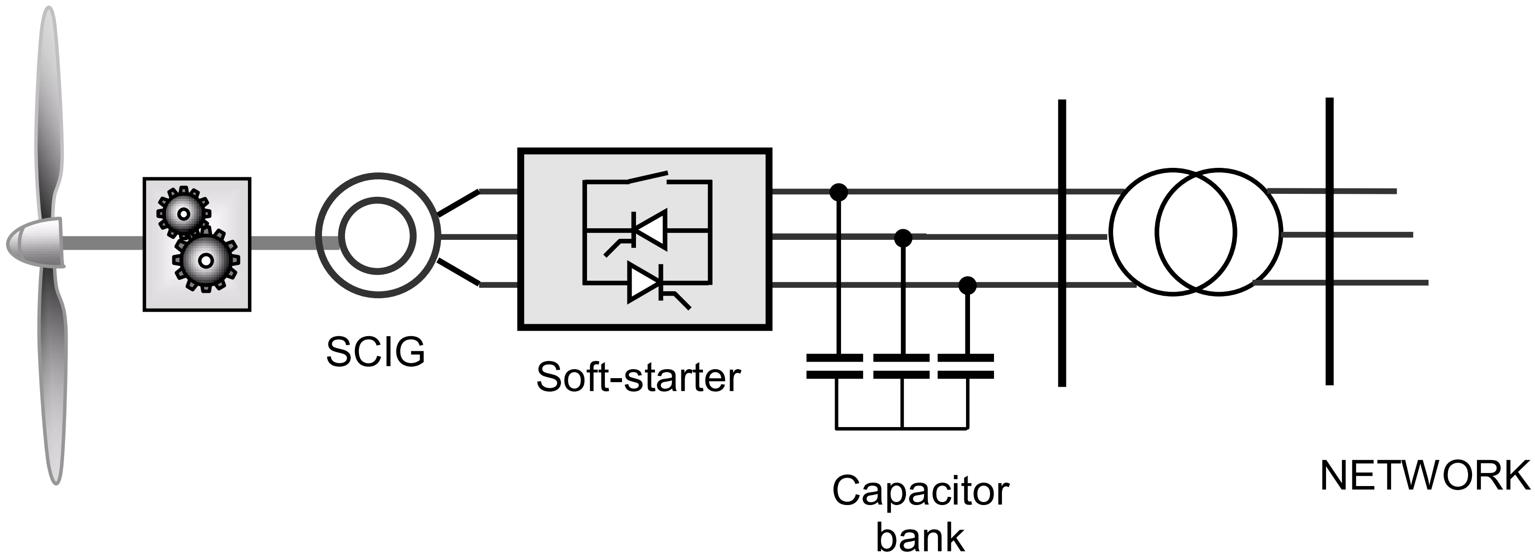
Combination of mechanical and electrical systems

Mechanical:
Aerodynamics and structural dynamics

Electrical:
Generator, power electronic converters, control system, protection equipment

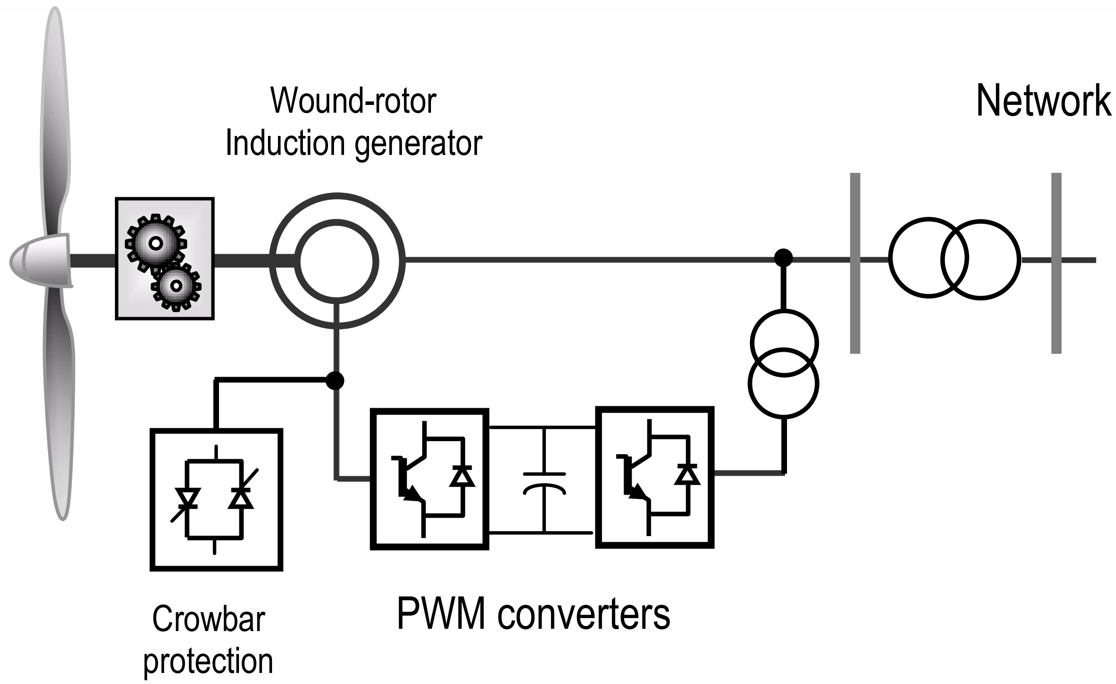
2. Wind turbine technologies

FSIG-based wind turbine



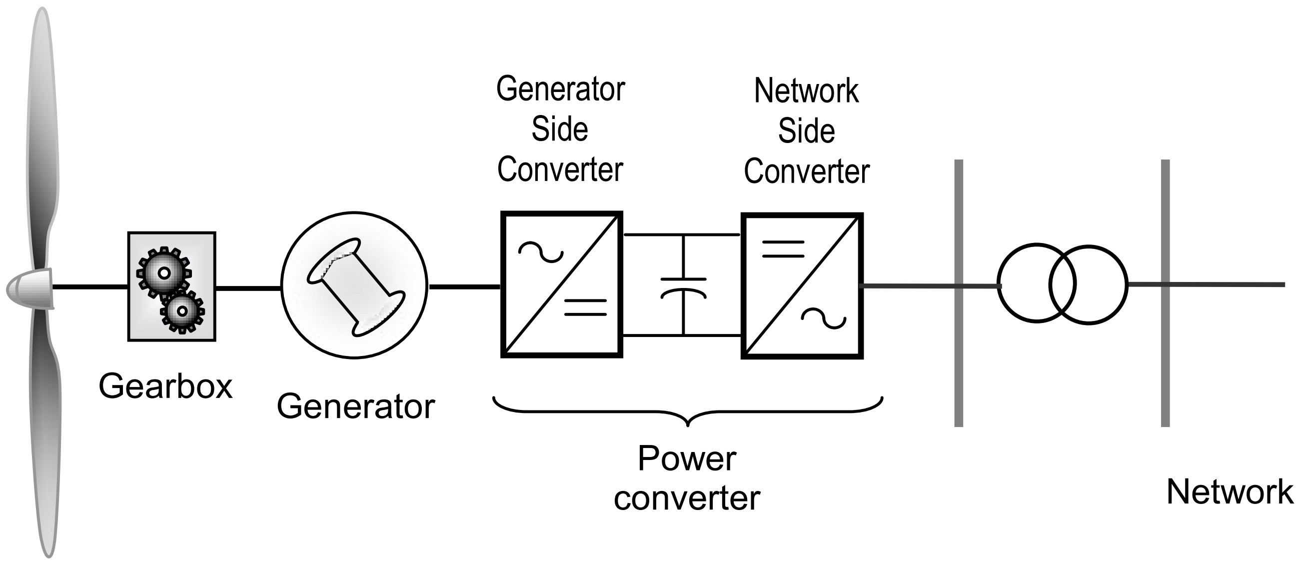
- Fixed-Speed Induction Generator (FSIG)-based wind turbines employ a squirrel-cage induction generator directly connected to the network.
- The slip (and hence the rotor speed) varies with the amount of power generated. In this turbines the rotor speed variations are very small (1 or 2%).
- The induction generator consumes reactive power and hence capacitor banks are used to provide the reactive power consumption and to improve the power factor.
- An anti-parallel thyristor soft-start unit is used to energise the generator once its operating speed is reached.
- Power control is typically exercised through pitch control.

DFIG-based wind turbine



- Doubly-Fed Induction Generator (DFIG)-based wind turbines employ a wound rotor induction generator with slip rings to take current into or out of the rotor.
- Variable-speed operation is obtained by injecting a controllable voltage into the rotor at slip frequency.
- The rotor winding is fed through a variable frequency power converter. The power converter decouples the network electrical frequency from the rotor mechanical frequency enabling the variable-speed operation of the wind turbine.
- The generator and converters are protected by voltage limits and an over-current 'crowbar'.

Wide-range SG wind turbine (SGWT)



- This wind turbine uses a synchronous generator (it can either be an electrically excited synchronous generator or a permanent magnet machine.
- The aerodynamic rotor and generator shafts may be coupled directly, or they can be couple through a gear box.
- To enable variable-speed operation, the synchronous generator is connected to the network through a variable frequency converter, which completely decouples the generator from the network.
- The electrical frequency of the generator may vary as the wind speed changes, while the network frequency remains unchanged.
- The rating of the power converter in this wind turbine corresponds to the rated power of the generator plus losses.

3. Optimum power extraction from wind

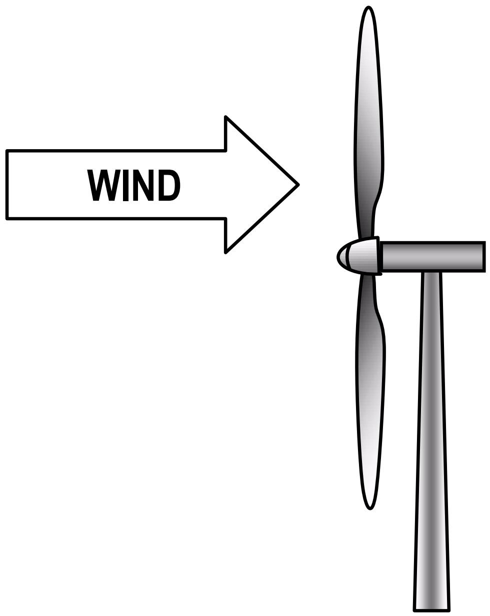
Optimum power extraction from wind

Power in the airflow:

$$P_{air} = \frac{1}{2}\rho A U^3$$

Power extracted by the wind turbine rotor:

$$P_{wt} = C_p \cdot P_{air}$$



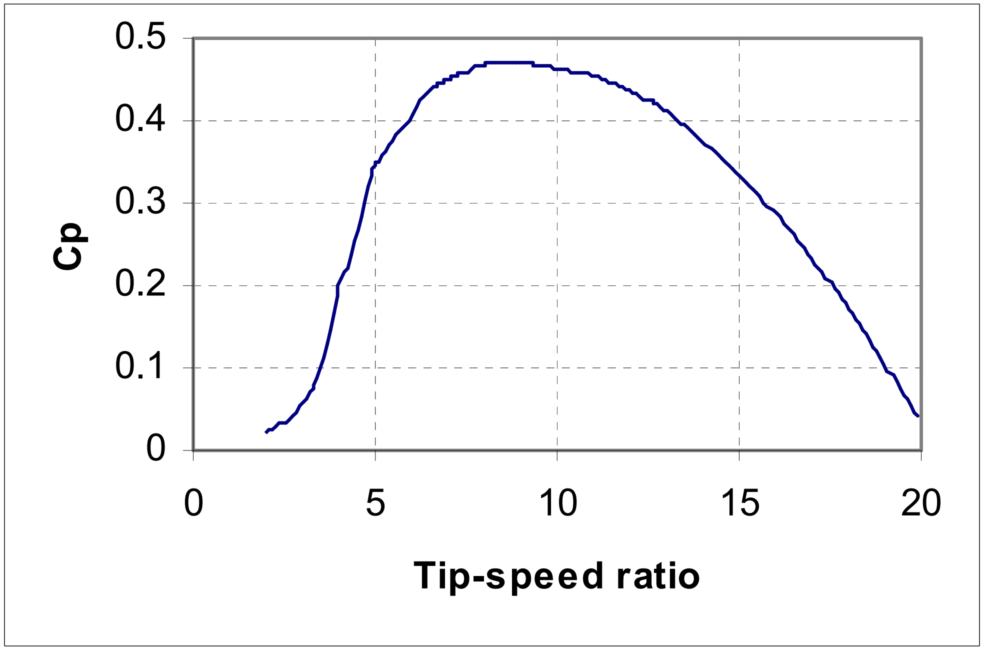
$$C_{p\max} = 0.593$$ **(Betz limit)**

Where:

- ρ : Air density
- A : Area swept by the blades
- U : Wind speed
- C_p : Power coefficient

The turbine will never extract more than 59% of the power from the airflow

Optimum power extraction from wind



Power coefficient/Tip speed ratio curve

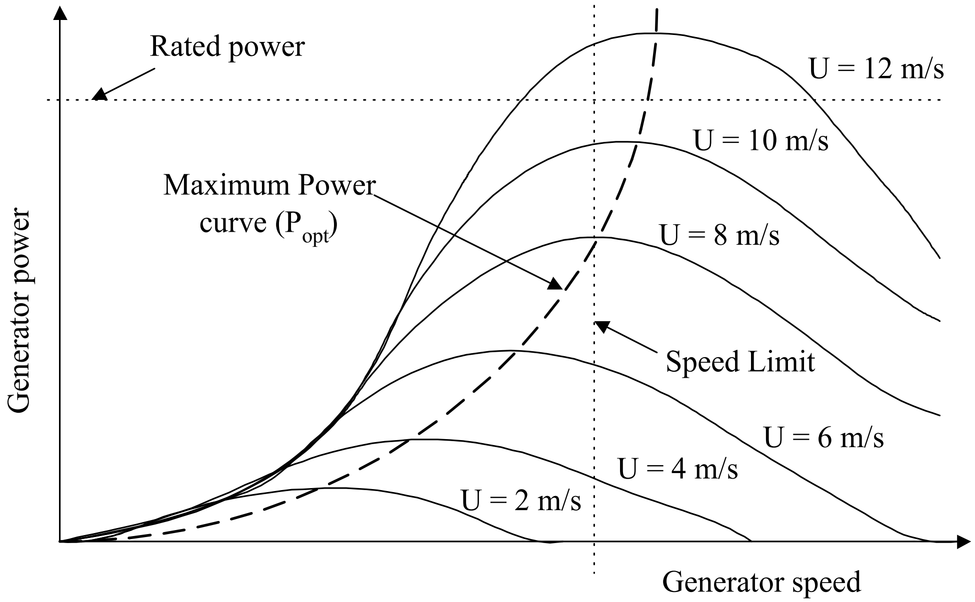
Tip speed ratio λ:

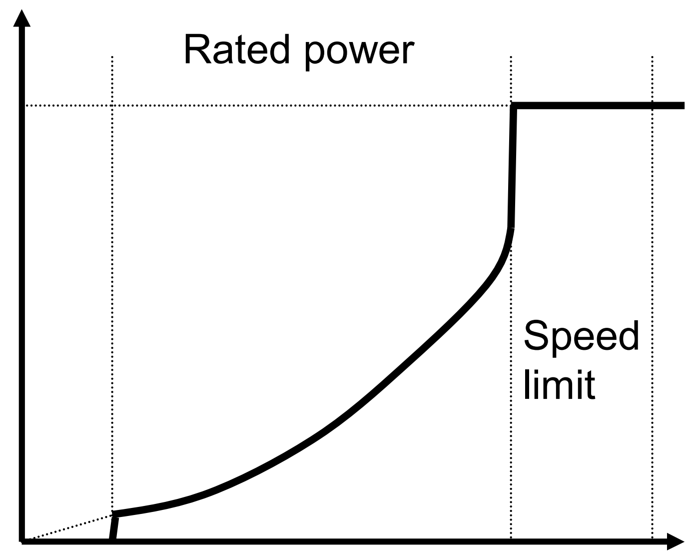
$$\lambda = \frac{\omega_r R}{U}$$

ω_r is the rotor speed and R is the radius of the rotor

- **To extract maximum power ω_r should vary with the wind speed such as to maintain λ at its λ_{opt}**
- **Operating a wind turbine at variable rotational speed it is possible to operate at maximum C_p over a wide range of wind speeds**

Wind turbine power curve

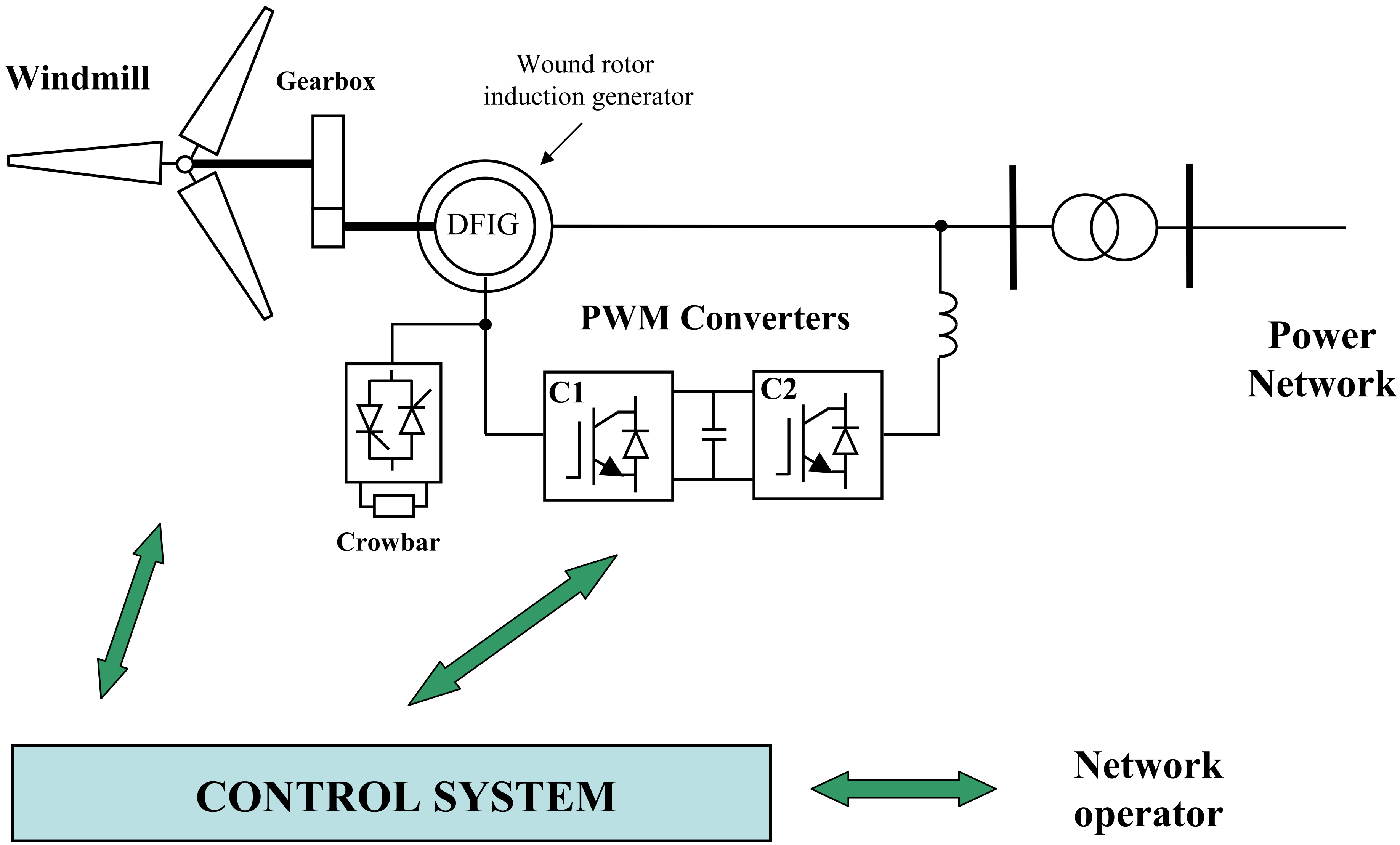




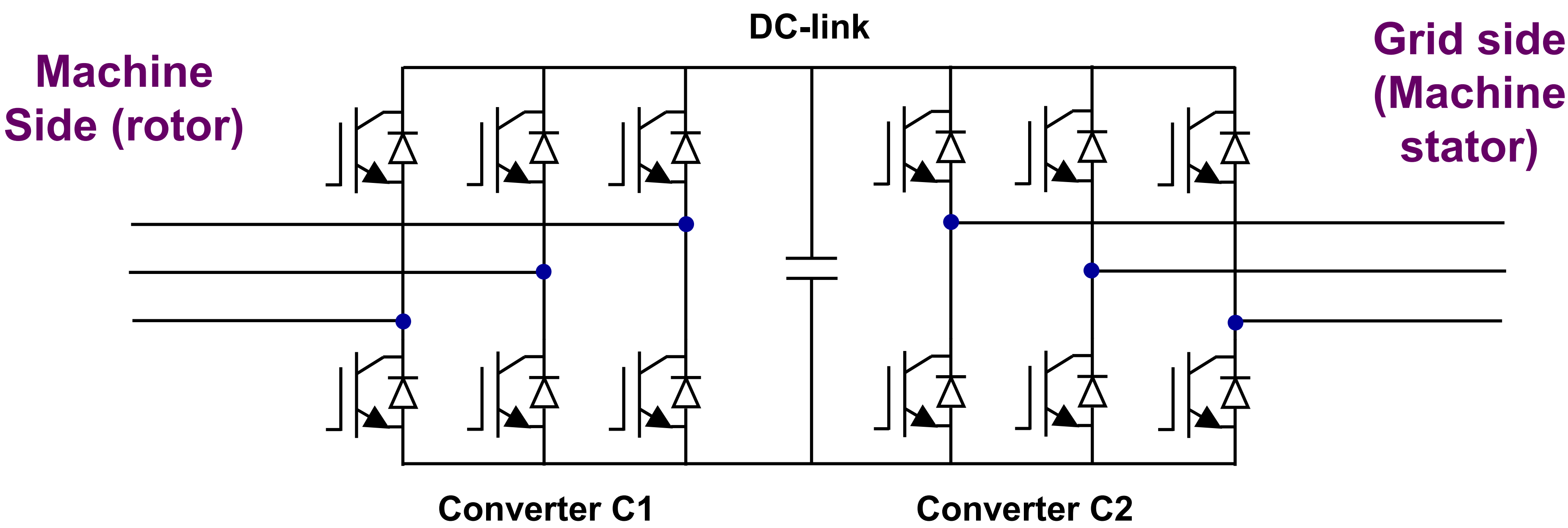
- In practice the rotor torque (power) is used as set-point and a speed controller is designed to maintain the operation of the generator at the point of maximum power extraction

4. Dynamic model of the Doubly-Fed Induction Generator (DFIG)

Typical DFIG wind turbine



DFIG power electronic converters



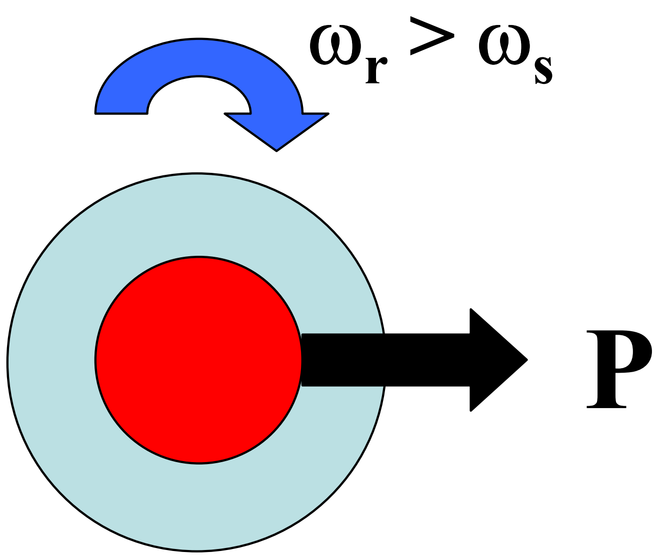
Back-to-back voltage source converters (VSCs)

- Graetz bridge (two-level VSC)
- IGBT-based
- Pulse Width Modulated (Sinusoidal, Space Vector PWM)
- Typical switching frequencies above 2 kHz
- Trade-off between switching frequency (losses) and harmonics

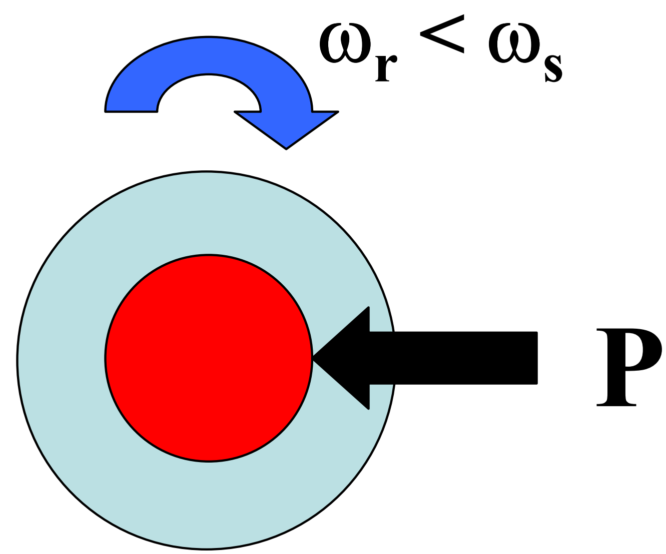
DFIG power relationships

A DFIG system can deliver power to the grid through the stator and rotor, while the rotor can also absorb power. This is dependent upon the rotational speed of the generator

$$s = \frac{\omega_s - \omega_r}{\omega_s}$$

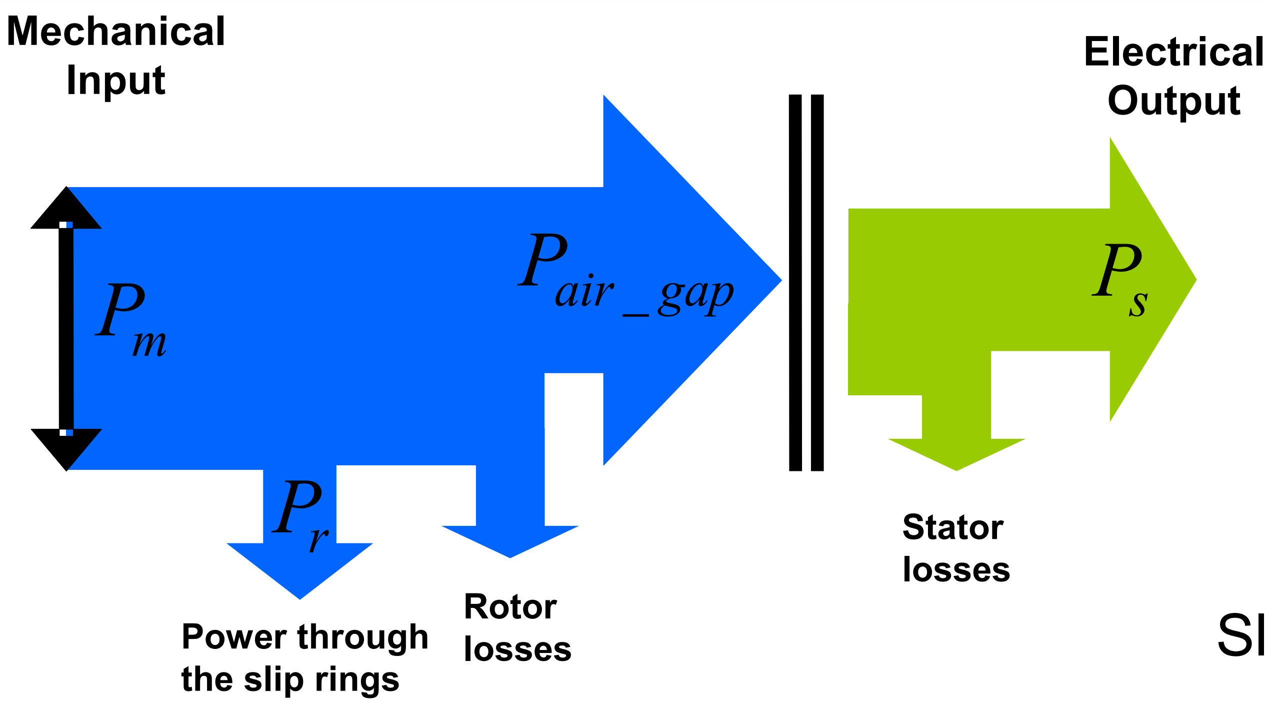


Super synchronous operation



Sub synchronous operation

DFIG power relationships



$$P_{air\_gap} = P_s$$

$$P_{air\_gap} = P_m - P_r = P_s$$

$$P_s = P_m - P_r$$

$$T\omega_s = T\omega_r - P_r$$

Slip → $s = \dfrac{\omega_s - \omega_r}{\omega_s}$

P_m : Mechanical power delivered to the generator

P_r : Power delivered by the rotor

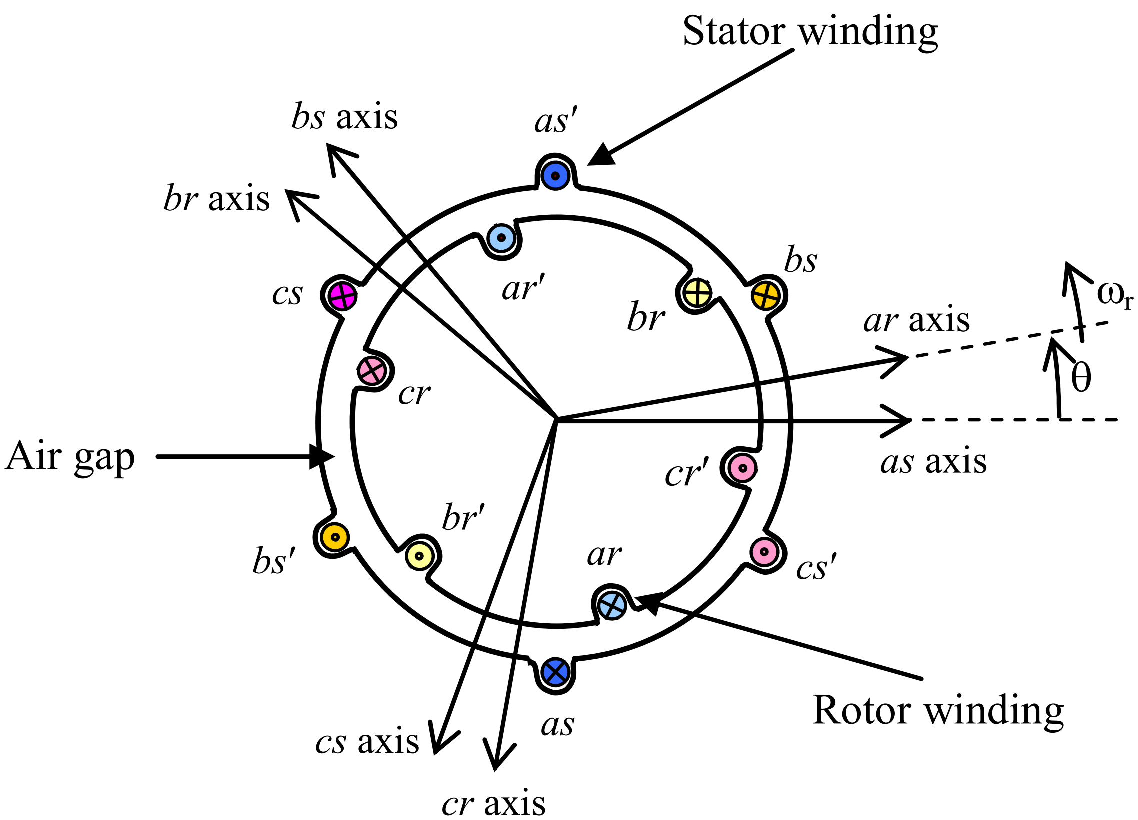
P_{air_gap} : Power at the generator's air gap

P_s : Power delivered by the stator

$$P_r = -Ts\omega_s = -sP_s$$

$$P_g = P_s + P_r$$

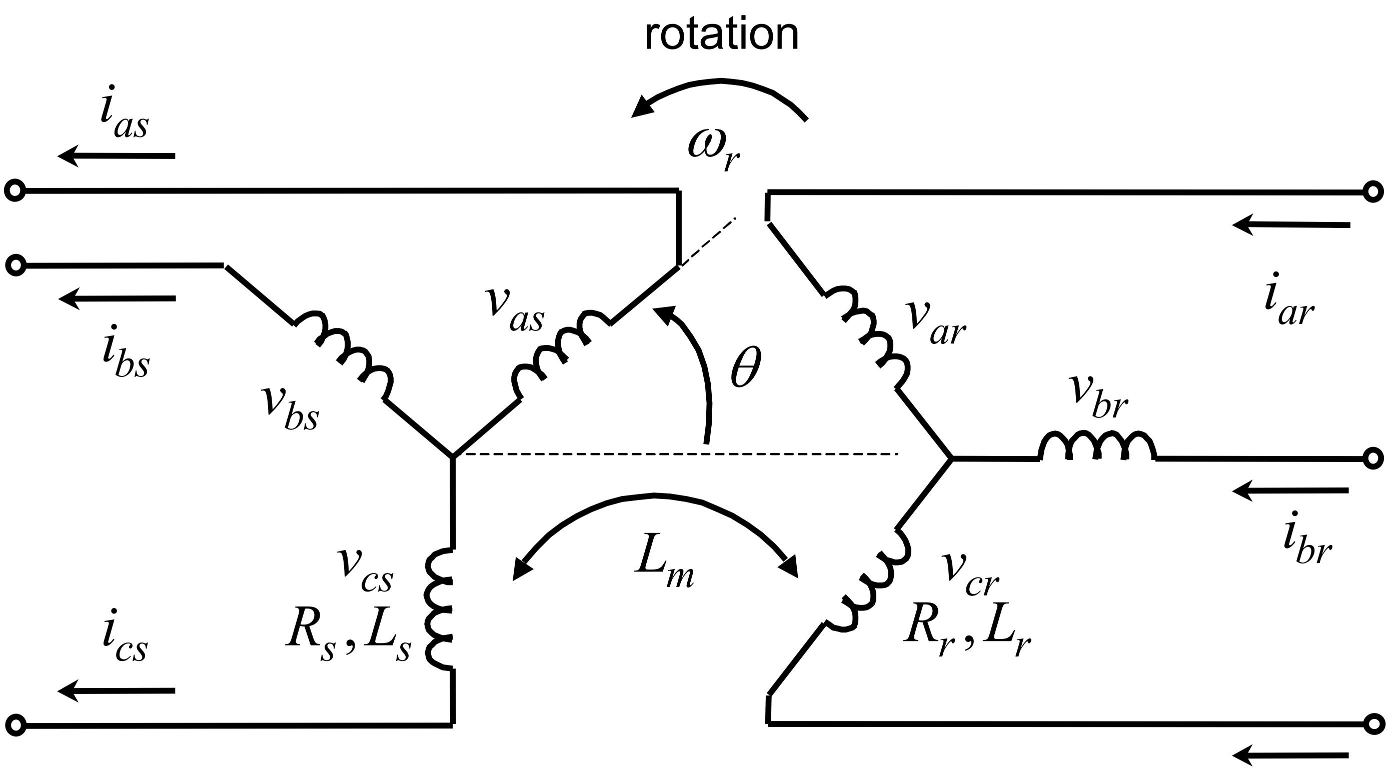
Dynamic model of the DFIG



Schematic diagram of an induction generator

- Derive voltage and flux equations for the stator and rotor in the *abc* domain.
- Transform voltage and flux equations to the *dq* reference frame.
- Model the induction generator as a voltage behind a transient reactance.

Stator and rotor circuits of an induction generator



R_s : Stator resistance

R_r : Rotor resistance

L_s : Stator leakage inductance

L_r : Rotor leakage inductance

L_m : Magnetising inductance

$$L_{ss} = L_s + L_m$$

$$L_{rr} = L_r + L_m$$

L_{ss}, L_{rr} : Stator and rotor self-inductances

DFIG 3rd order model
(voltage behind transient reactance)

Stator voltages:

$$\begin{cases} \bar{v}_{ds} = -\bar{R}_s \bar{i}_{ds} + \bar{X}' \bar{i}_{qs} + \bar{e}_d \\ \bar{v}_{qs} = -\bar{R}_s \bar{i}_{qs} - \bar{X}' \bar{i}_{ds} + \bar{e}_q \end{cases}$$

Rotor voltages:

$$\begin{cases} \dfrac{d\bar{e}_d}{dt} = -\dfrac{1}{\omega_s T_o}\left[\bar{e}_d - \left(\bar{X} - \bar{X}'\right)\bar{i}_{qs}\right] + s\omega_s \bar{e}_q - \omega_s \dfrac{\bar{L}_m}{\bar{L}_{rr}} \bar{v}_{qr} \\ \dfrac{d\bar{e}_q}{dt} = -\dfrac{1}{\omega_s T_o}\left[\bar{e}_q + \left(\bar{X} - \bar{X}'\right)\bar{i}_{ds}\right] - s\omega_s \bar{e}_d + \omega_s \dfrac{\bar{L}_m}{\bar{L}_{rr}} \bar{v}_{dr} \end{cases}$$

Voltage components:

$$\bar{e}_d = -\frac{\bar{L}_m}{\bar{L}_{rr}} \bar{\psi}_{qr} \qquad \bar{e}_q = \frac{\bar{L}_m}{\bar{L}_{rr}} \bar{\psi}_{dr}$$

Transient reactance's:

$$\bar{X} = \bar{X}_s + \bar{X}_m \qquad \bar{X}' = \bar{X}_s + \frac{\bar{X}_r \times \bar{X}_m}{\bar{X}_r + \bar{X}_m}$$

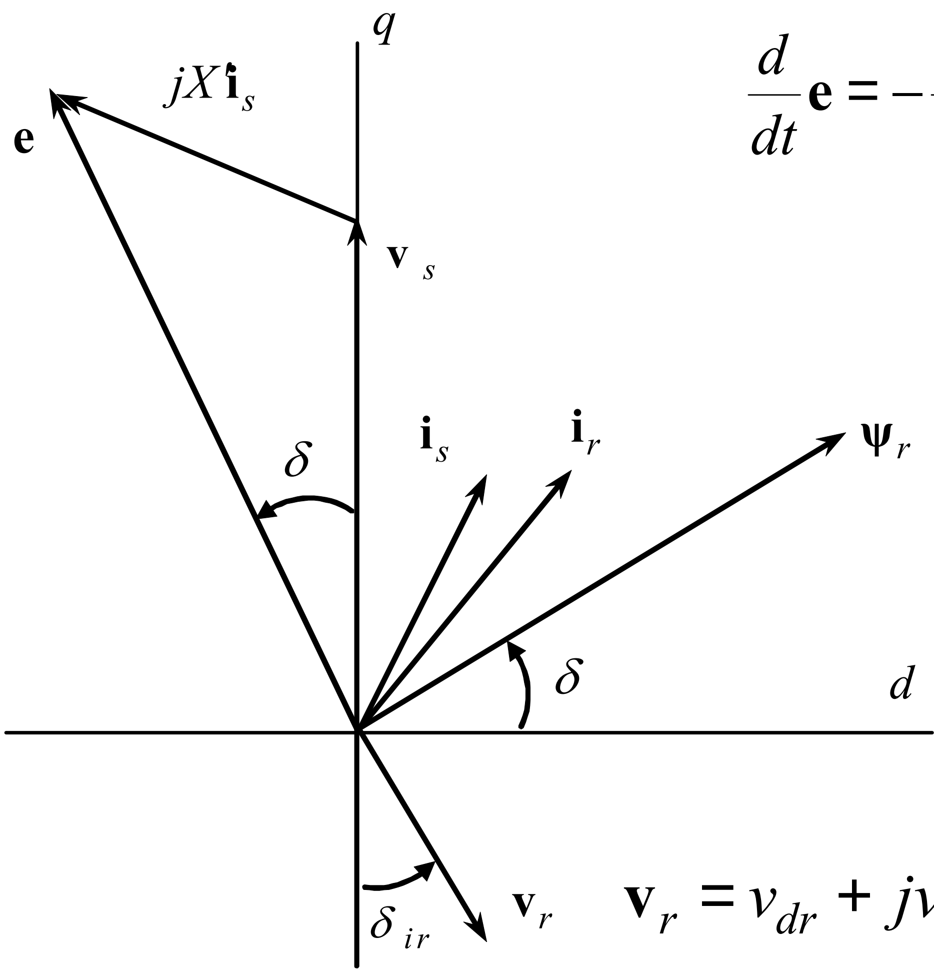
Open circuit time constant:

$$\bar{T}_o = \frac{\bar{L}_{rr}}{\bar{R}_r} = \frac{\bar{L}_r + \bar{L}_m}{\bar{R}_r}$$

Rotor swing equation:

$$\frac{d\omega_r}{dt} = \frac{1}{J} \times \left(T_m - T_e\right) \qquad \bar{T}_e = \frac{\left(\bar{e}_d \times \bar{i}_{ds} + \bar{e}_q \times \bar{i}_{qs}\right)}{\bar{\omega}_s}$$

Vector diagram of DFIG operating conditions



$$\mathbf{v}_r = v_{dr} + jv_{qr}$$

$$\frac{d}{dt}\mathbf{e} = -\frac{1}{\omega_s T_o}\left[\mathbf{e} - j\left(X - X'\right)\mathbf{i}_s\right] + j\omega_s s\mathbf{e} - j\omega_s \frac{L_m}{L_{rr}}\mathbf{v}_r$$

In steady state $d\mathbf{e}/dt = 0$

$$s\mathbf{e} \approx \frac{L_m}{L_{rr}}\mathbf{v}_r$$

$$\mathbf{v}_r \approx s\mathbf{e}$$

e : internal voltage vector
$\mathbf{v_s}$: terminal voltage vector
$\mathbf{\Psi_r}$: rotor flux vector
$\mathbf{v_r}$: rotor voltage vector

5. Control of DFIG-based wind turbines

Decoupled active and reactive power control

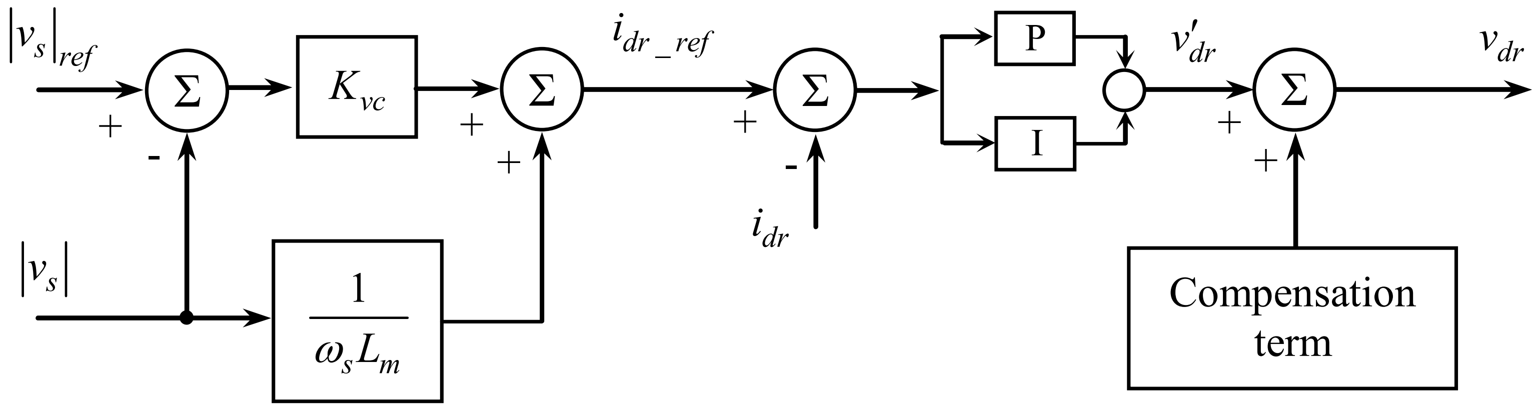
- The dq transformation allows the two rotor injection voltages v_{qr} and v_{dr} to be regulated separately

- Power control $\longrightarrow$ v_{qr}

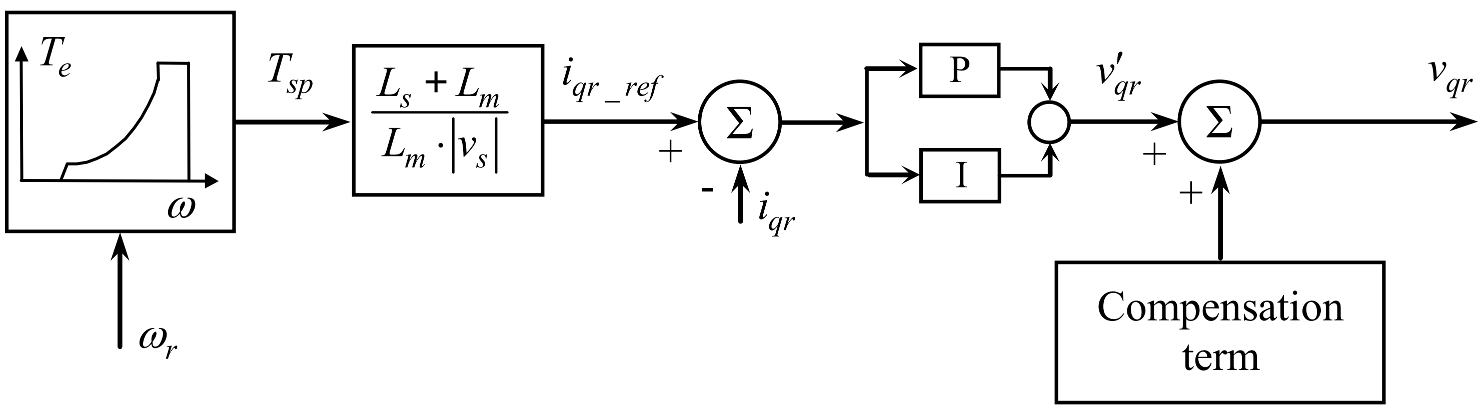
- Voltage control $\longrightarrow$ v_{dr}

DFIG current-mode control

Voltage control loop:



Torque control loop:



Source: Ref [4]

DFIG rotor flux magnitude and angle control

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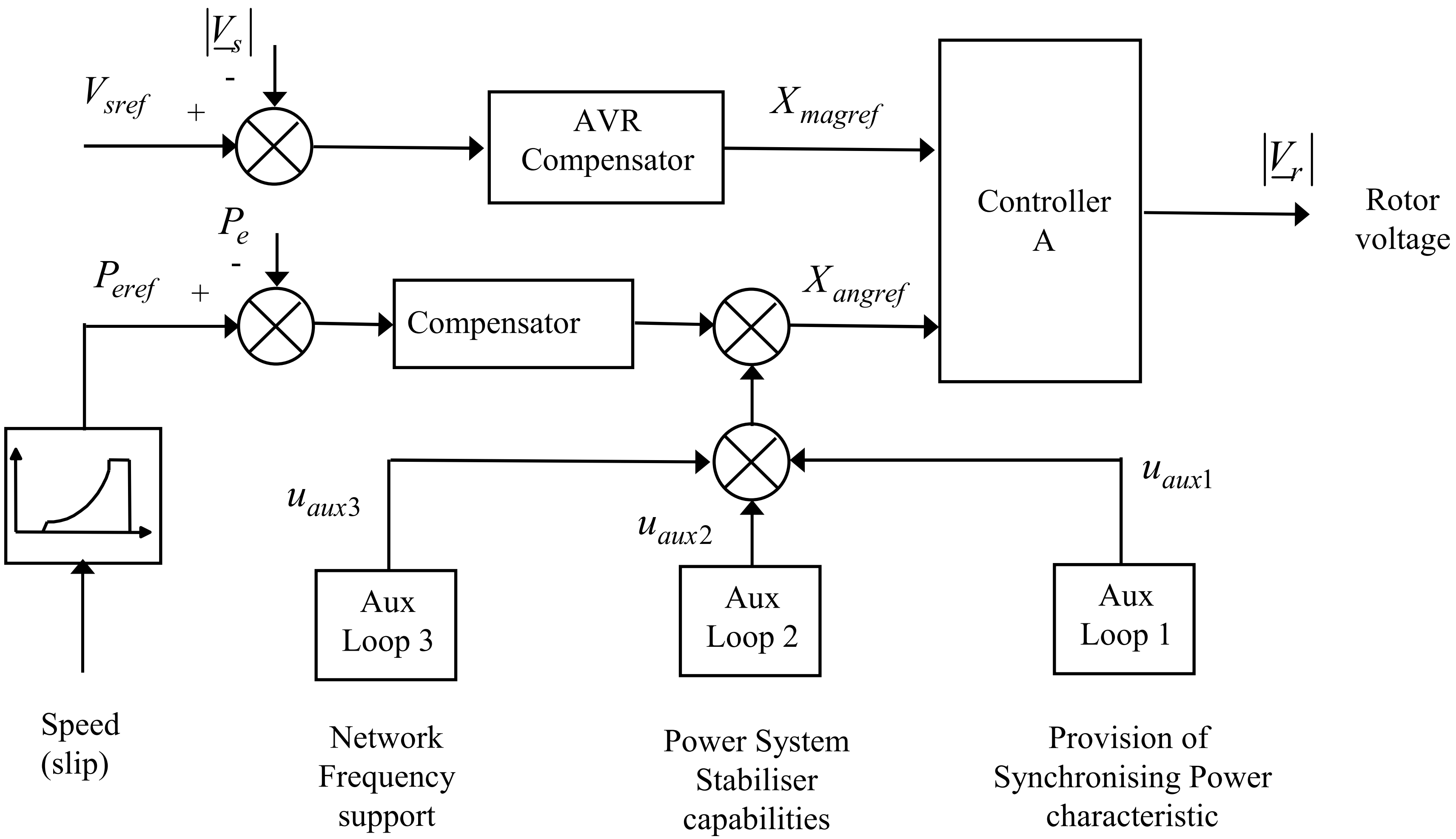
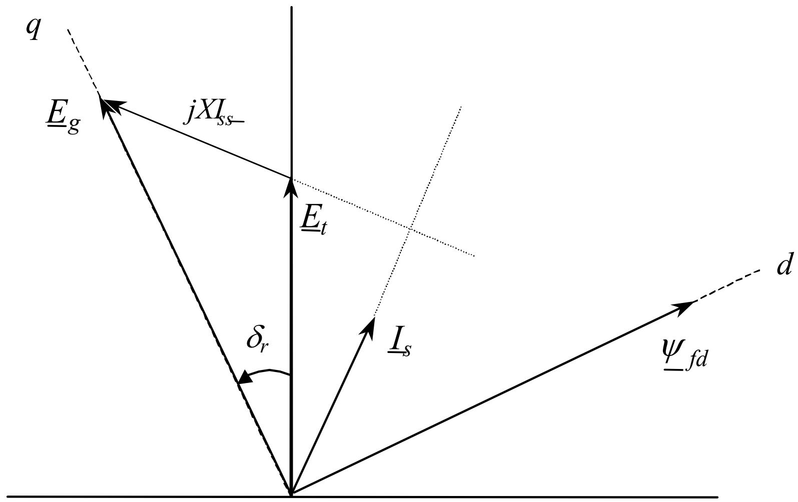


Flux and Magnitude Angle Controller (FMAC)

Source: Ref [3]

Synchronous Generator and DFIG vector diagrams

Round rotor synchronous generator



$\underline{\psi}_{fd}$ = rotor field flux vector

$|\underline{\psi}_{fd}| = E_{fd}$

E_{fd} = dc field voltage

$\underline{E}_t$ = terminal voltage vector

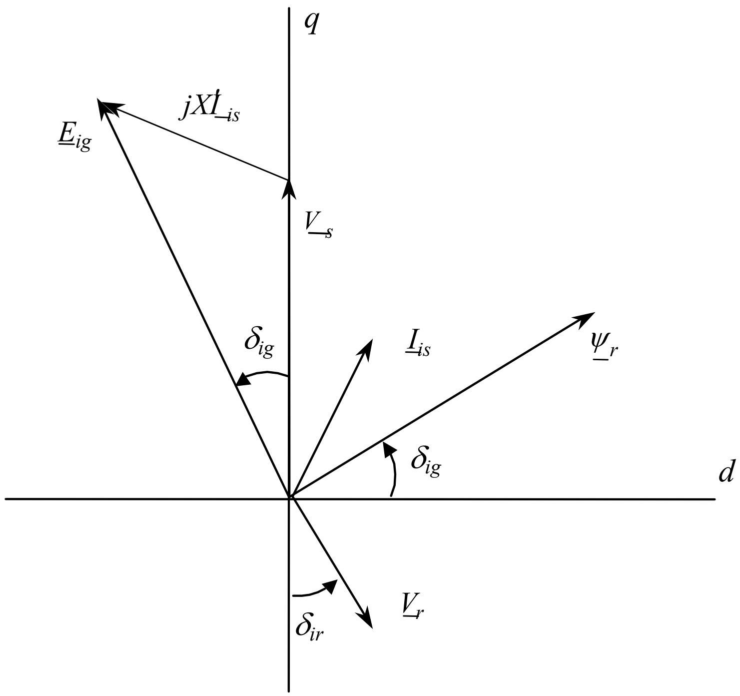
$\underline{E}_g$ = generator internal voltage (voltage behind synchronous reactance)

$\underline{I}_s$ = stator current vector

δ_r = rotor angle

X_S = synchronous reactance

Doubly fed induction generator



$\underline{\psi}_r$ = rotor flux vector

$\underline{V}_s$ = terminal voltage vector

$\underline{E}_{ig}$ = generator internal voltage vector (voltage behind transient reactance)

$\underline{I}_{is}$ = stator current vector

$\underline{V}_r$ = rotor voltage vector

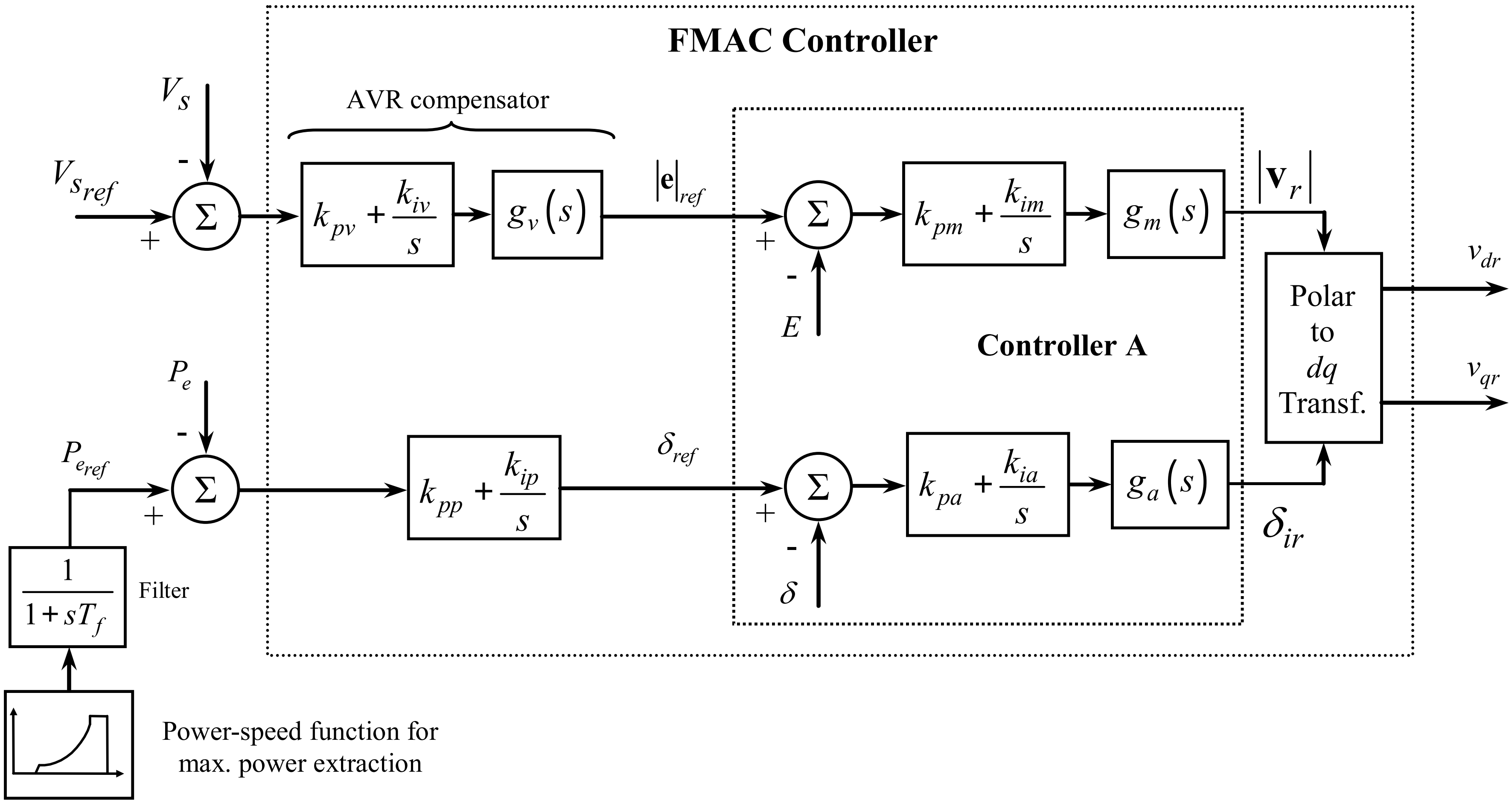
δ_{ig} = generator load angle

δ_{ir} = rotor voltage angle

X' = transient reactance

Source: Ref [3]

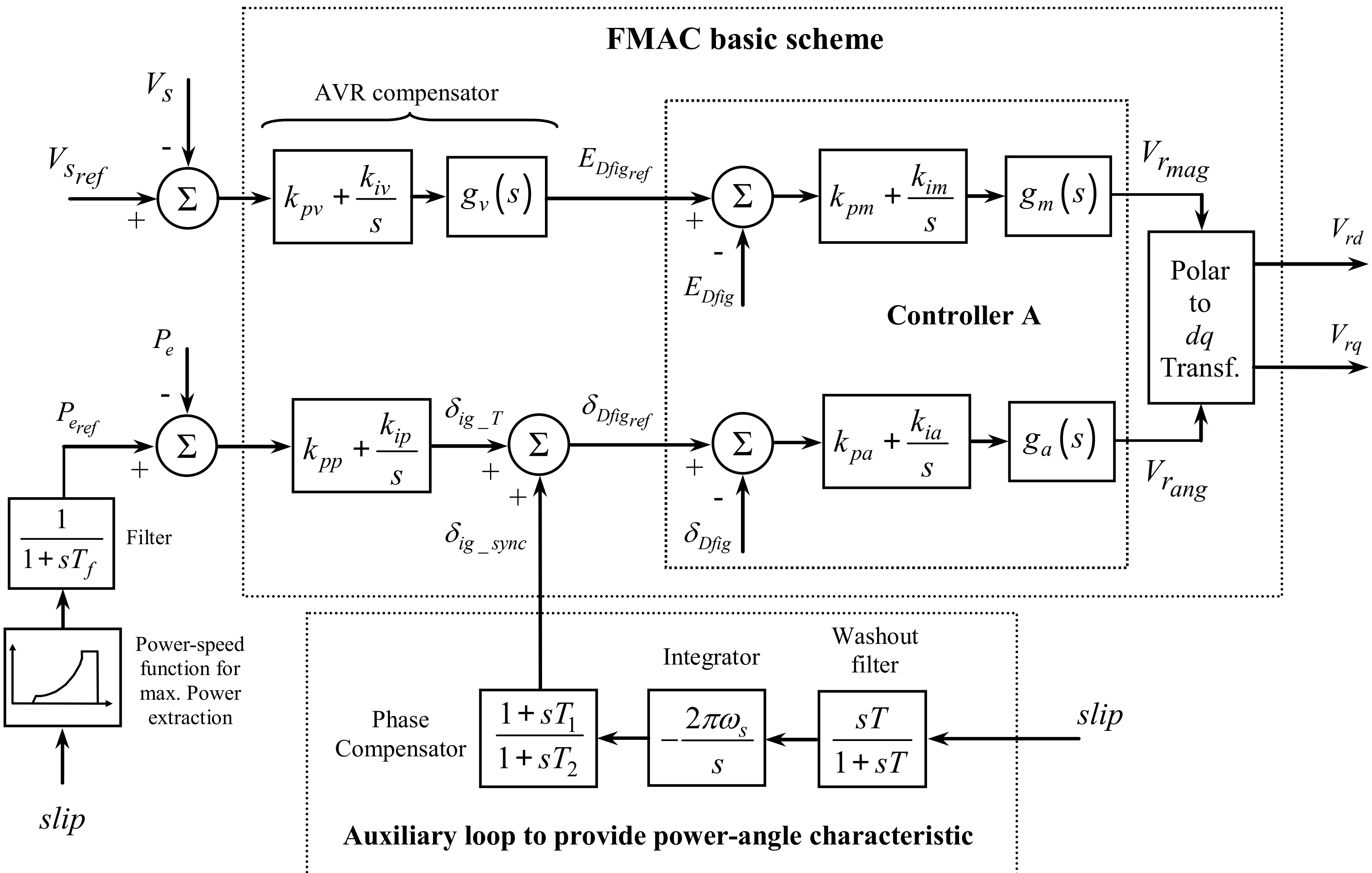
FMAC basic scheme



$$g_v(s) = \frac{1+0.024s}{1+0.004s} \cdot \frac{1+0.035s}{1+0.05s} \qquad g_m(s) = g_a(s) = \left(\frac{1+0.4s}{1+2s}\right)$$

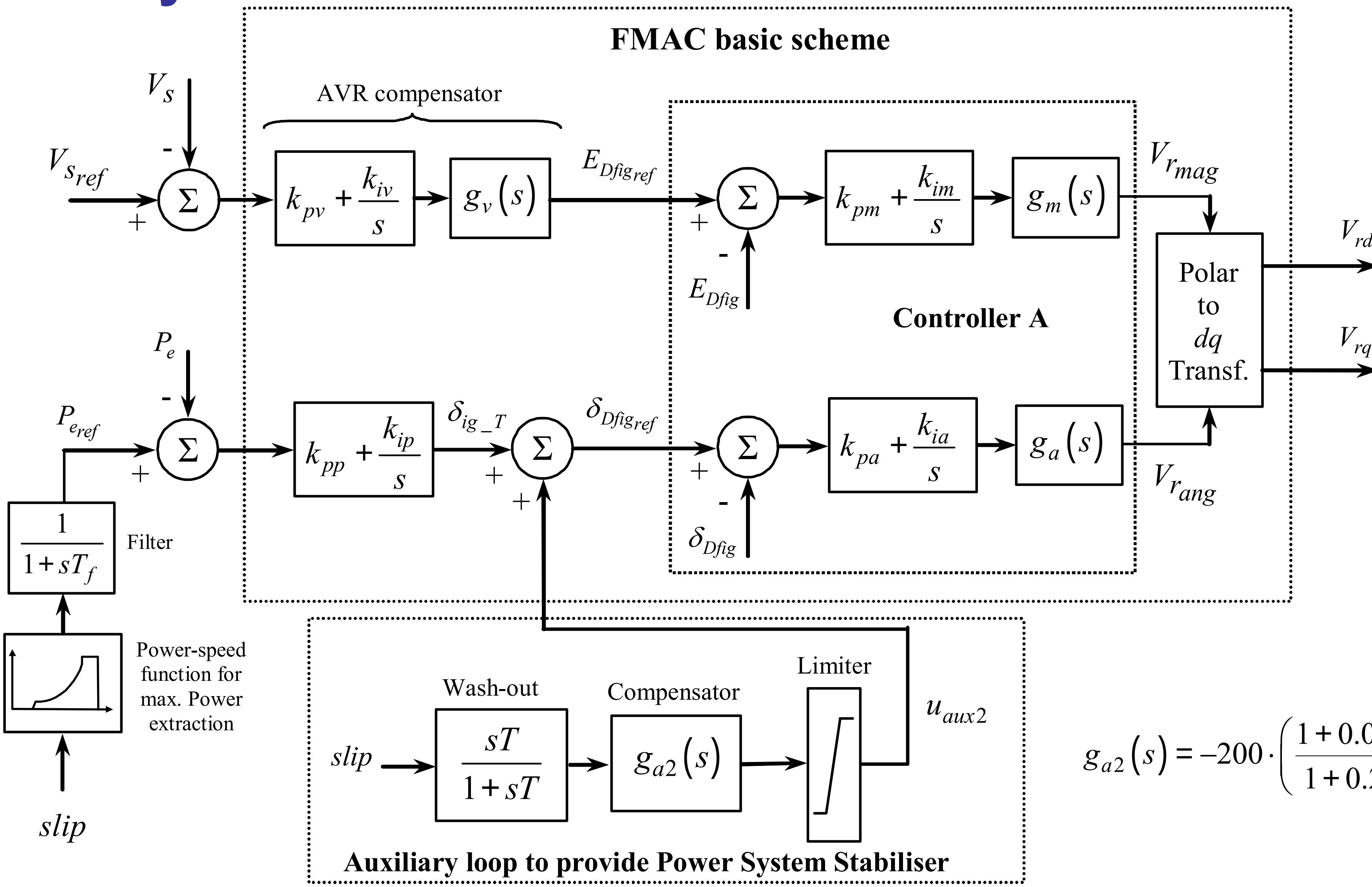
Source: Ref [3]

Auxiliary loop 1: Synchronising power characteristic



Source: Ref [3]

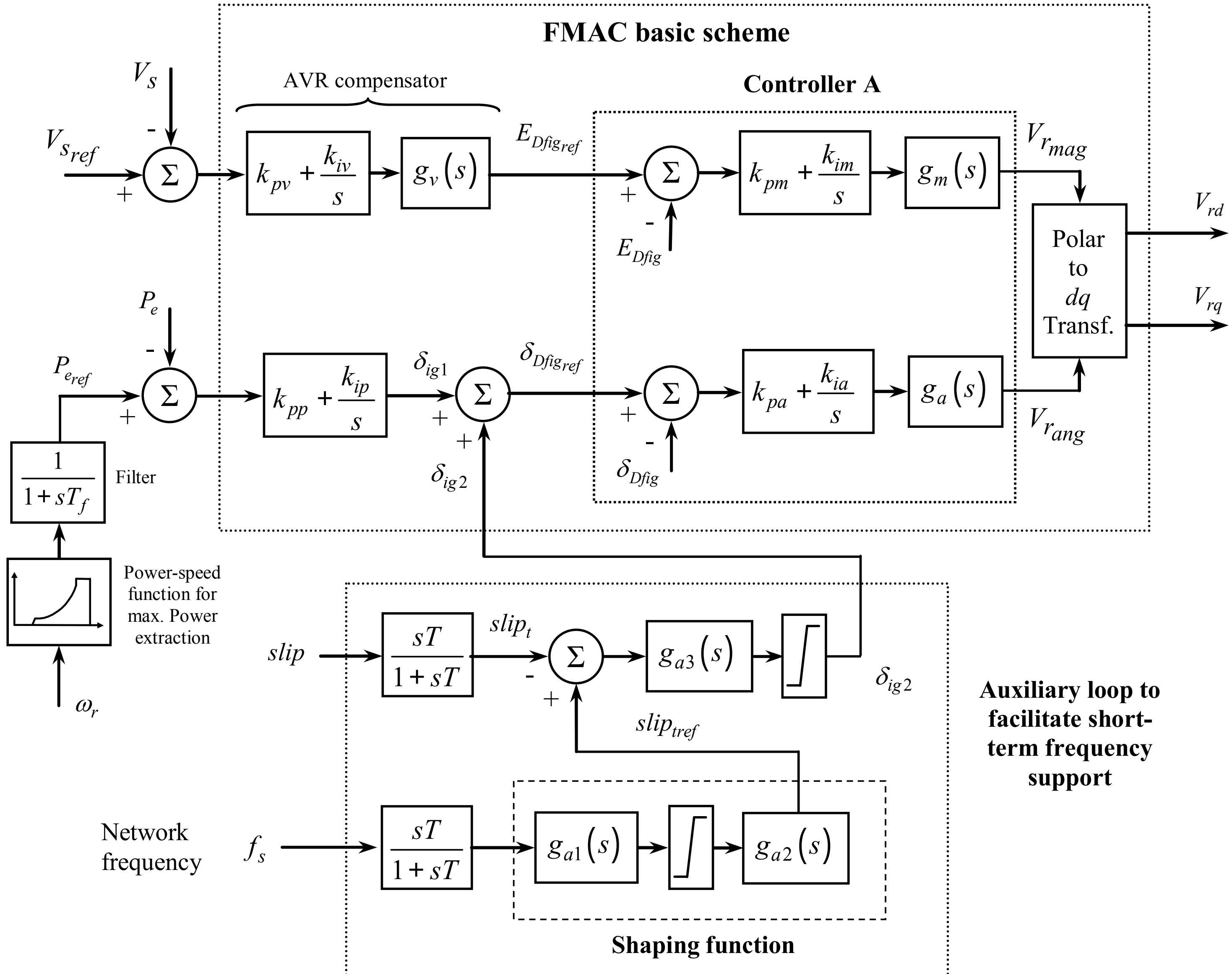
Auxiliary loop 2: Power System Stabiliser



$$g_{a2}(s) = -200 \cdot \left(\frac{1 + 0.04s}{1 + 0.2s} \right)^2$$

Source: Ref [3]

Auxiliary loop 3:
Short-term frequency regulation



$$g_{a1}(s) = \frac{-500}{1+5s}$$

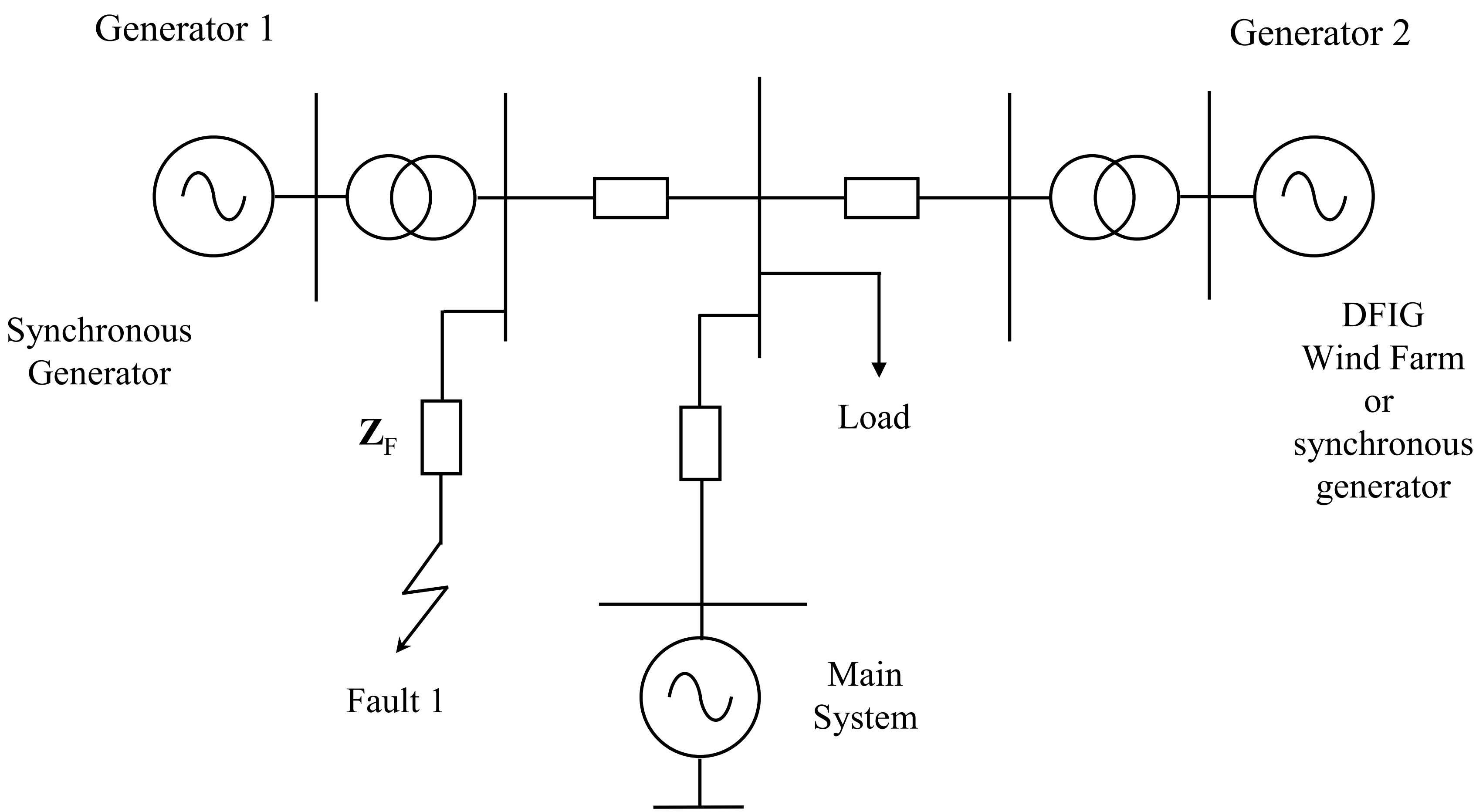
$$g_{a2}(s) = \frac{3+4.5s}{1+5s}$$

$$g_{a3}(s) = \frac{0.8+1.2s}{1+3s}$$

Source: Ref [3]

6. Impact of wind farms on transient and dynamic stability

Generic network model



Source: Ref [3]

Conventional synchronous plant operation

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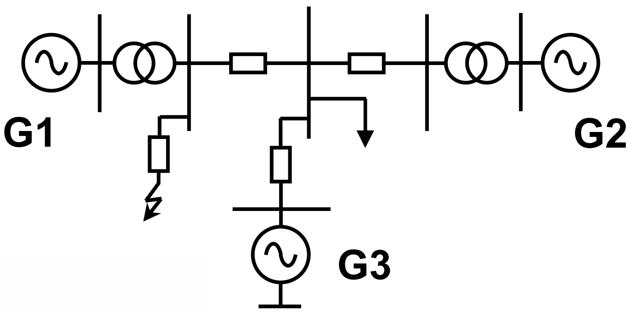
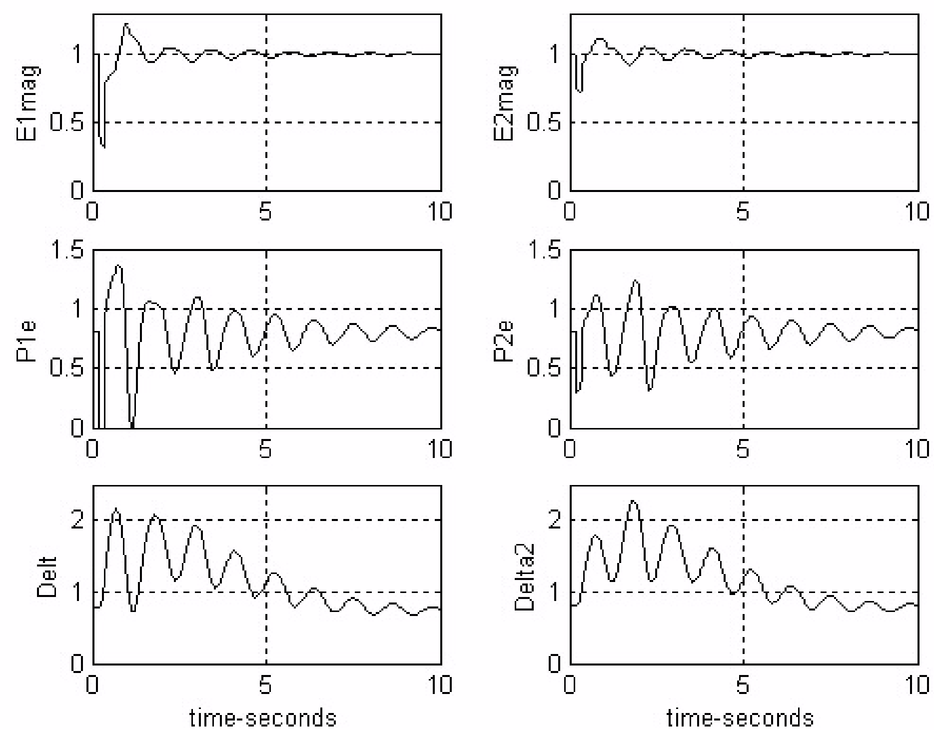
Generator 1 (G1): Synchronous generator
Generator 2 (G2): Synchronous generator



(a) Synchronous generator (G1)



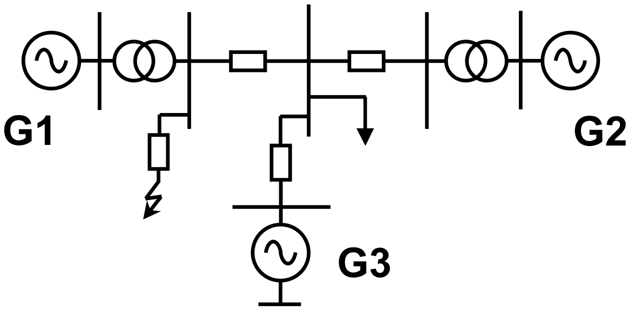
(b) Synchronous generator (G2)

FAULT 1 applied at t=0.2 s. Clearance time 150 ms.

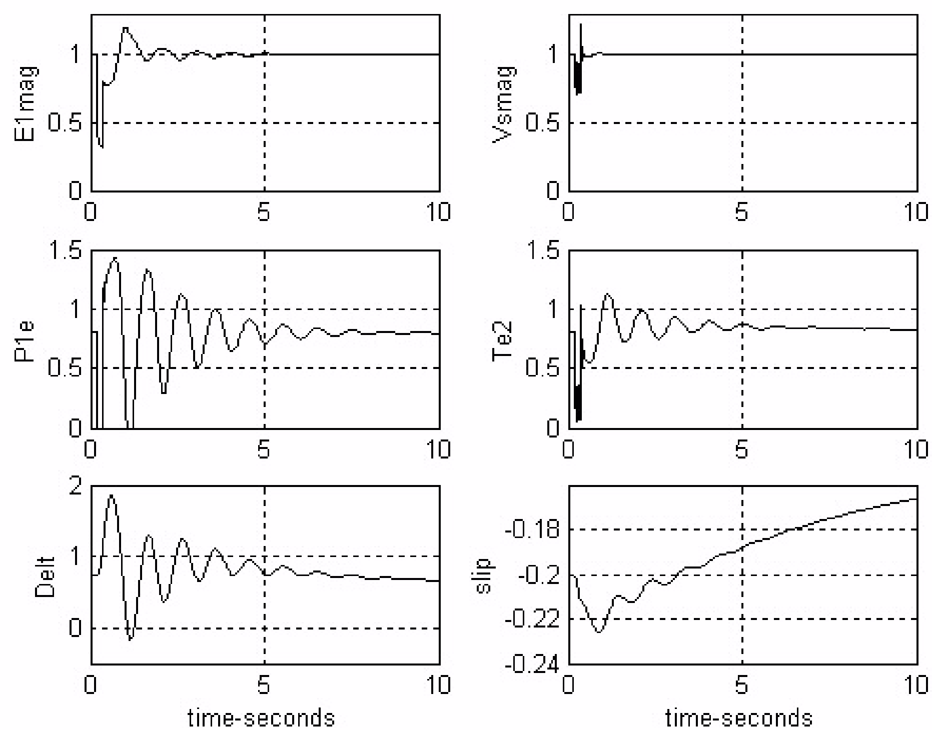
Source: Ref [3]

DFIG with synchronising power characteristic

Generator 1 (G1): Synchronous generator
Generator 2 (G2): DFIG with FMAC basic control



(a) Synchronous generator (G1)



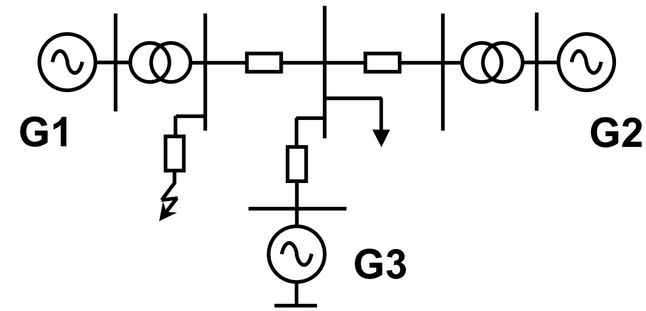
(b) DFIG wind farm (G2)

FAULT 1 applied at t=0.2 s. Clearance time 150 ms.

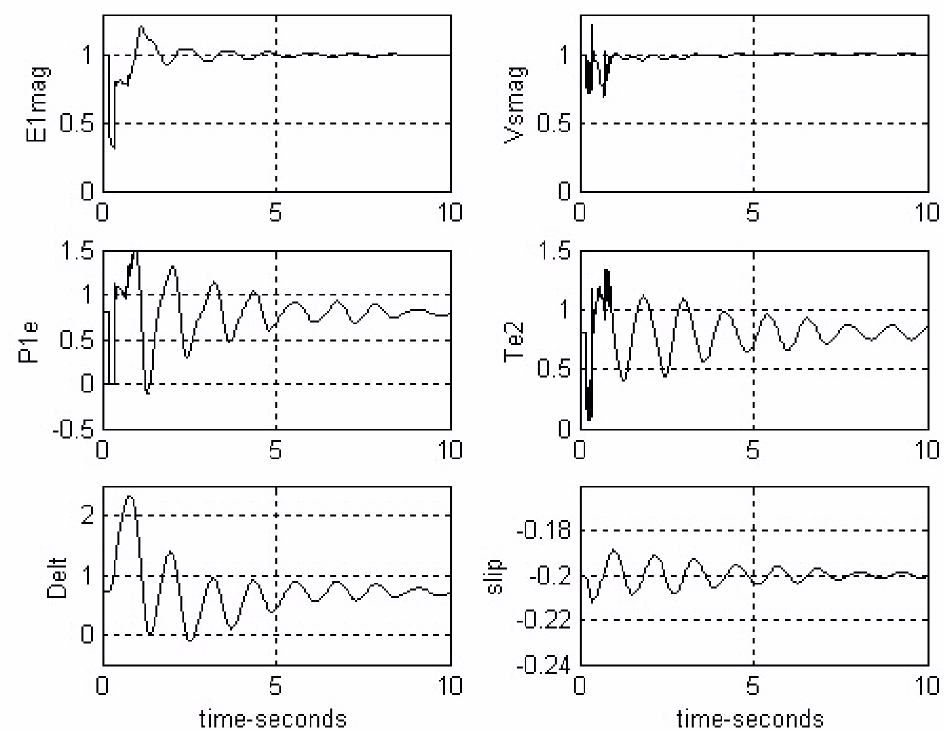
Source: Ref [3]

DFIG with synchronising power characteristic

Generator 1 (G1): Synchronous generator
Generator 2 (G2): DFIG with FMAC basic control scheme plus auxiliary loop 1.



(a) Synchronous generator (G1)



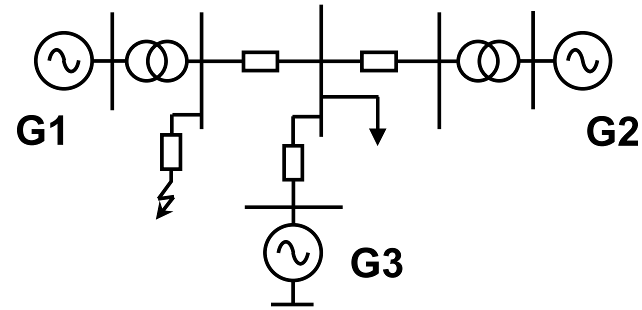
(b) DFIG wind farm (G2)

FAULT 1 applied at t=0.2 s. Clearance time 150 ms.

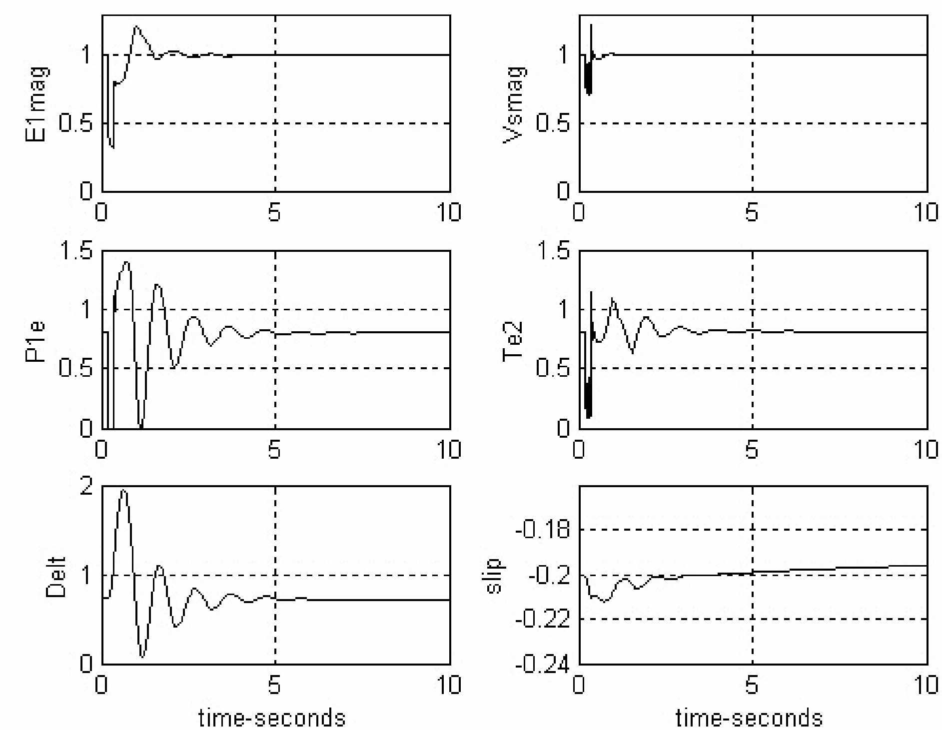
Source: Ref [3]

DFIG with PSS capability

Generator 1 (G1): Synchronous generator
Generator 2 (G2): DFIG with FMAC basic control scheme plus auxiliary loop 2



(a) Synchronous generator (G1)



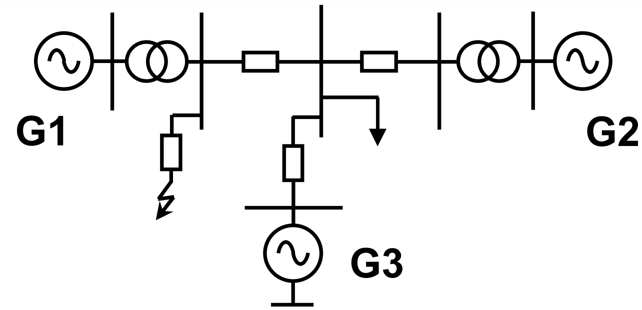
(b) DFIG wind farm (G2)

FAULT 1 applied at t=0.2 s. Clearance time 150 ms.

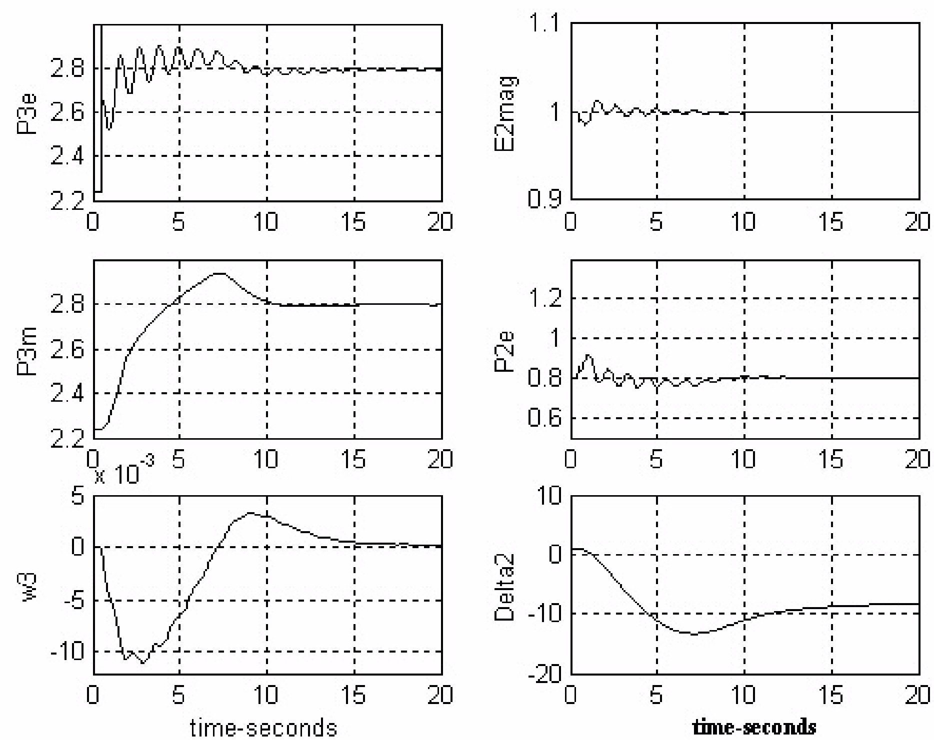
Source: Ref [3]

DFIG contribution to frequency regulation

Generator 1 (G1): Synchronous generator
Generator 2 (G2): Synchronous generator



(a) Main System (G3)



(b) Synchronous generator (G2)

Loss of generation applied at t=0.5 s.

Source: Ref [3]

DFIG contribution to frequency regulation

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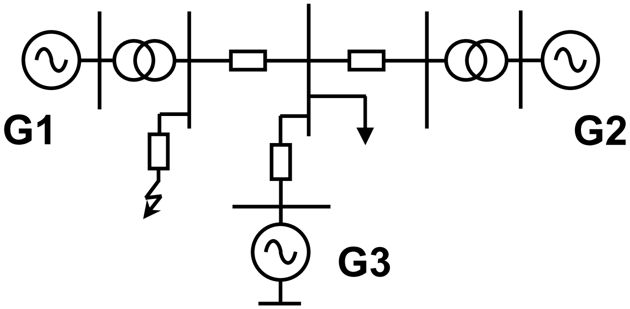
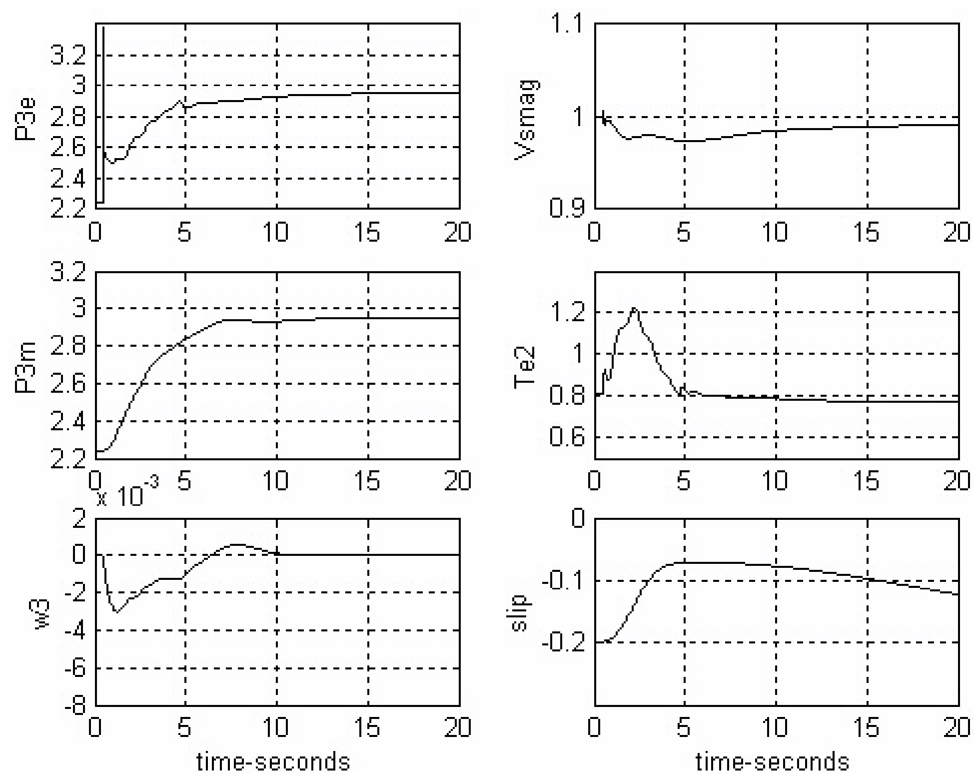
Generator 1 (G1): Synchronous generator
Generator 2 (G2): DFIG with FMAC basic control scheme plus auxiliary loop 3



(a) Main System (G3)



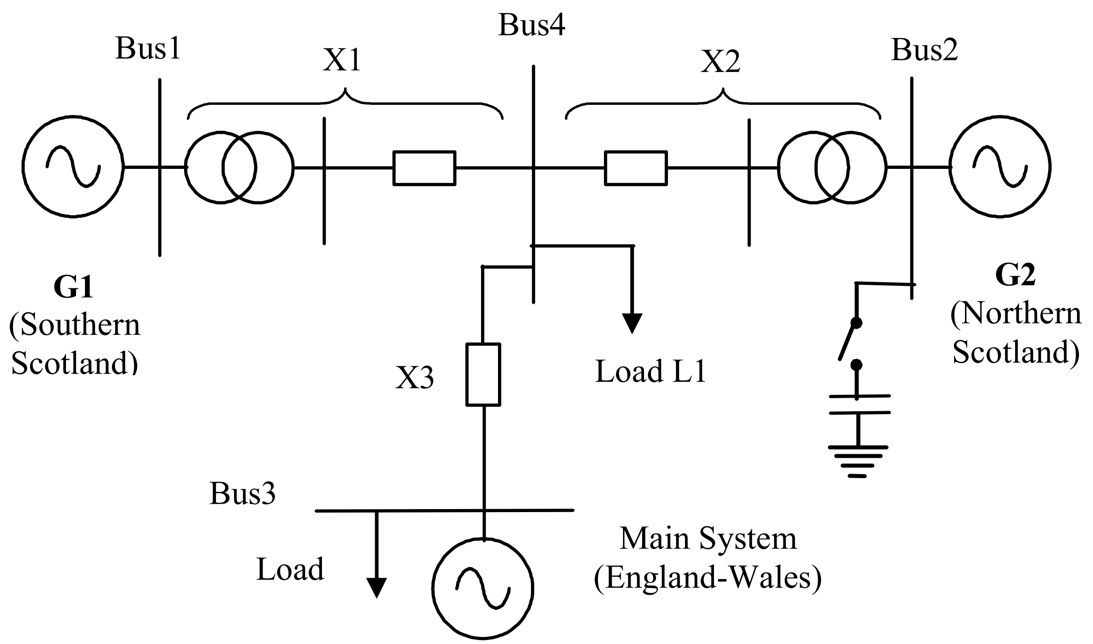
(b) DFIG wind farm (G2)

Loss of generation applied at t=0.5 s.

Source: Ref [3]

Influence of wind generation on dynamic stability

Eigenvalue analysis



Operating situations

Fixed power P1 of G1

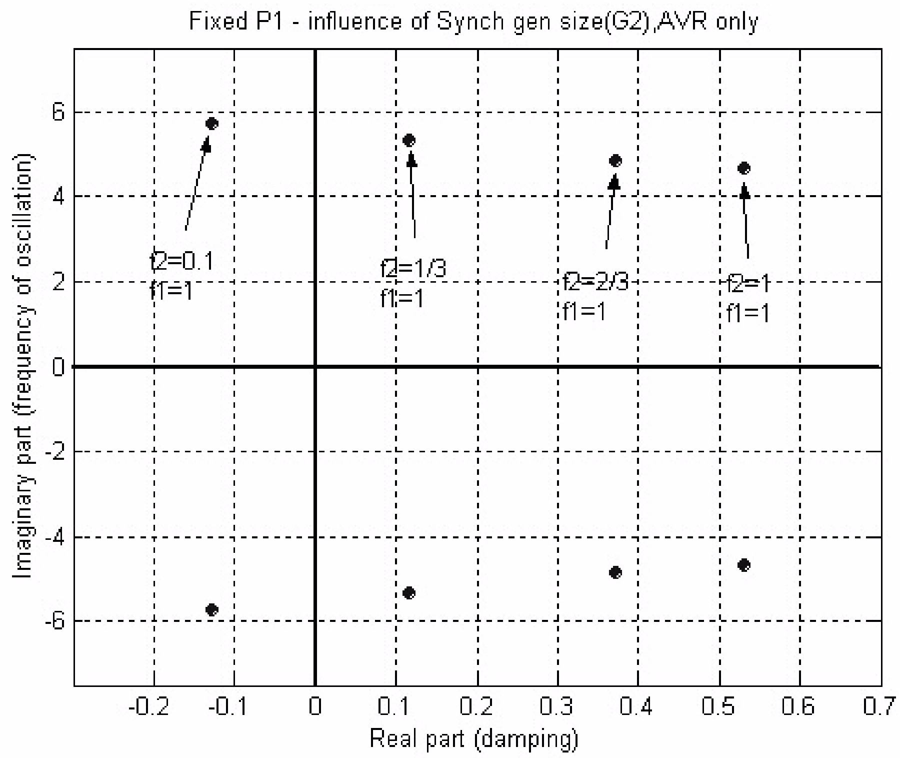
G2 f2	G1 Rating (MVA)	G1 Rating (MW)	G2 Rating (MVA)	G2 Rating (MW)
1	2,800	2,520	2,400	2,240
2/3	2,800	2,520	1,600	1,500
1/3	2,800	2,520	800	750
1/10	2,800	2,520	240	224

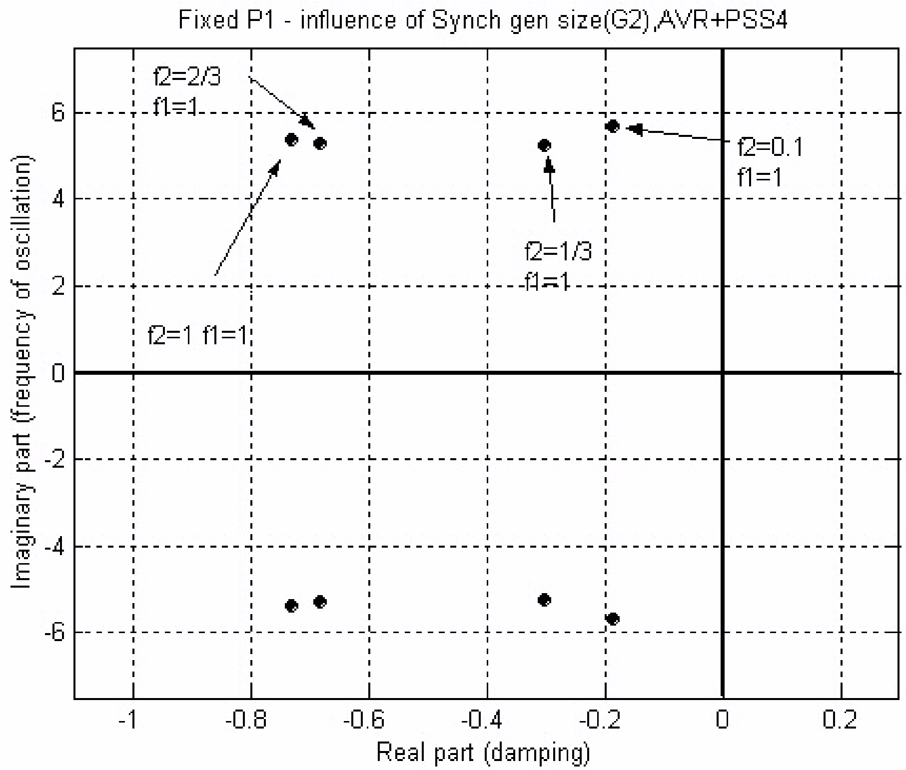
$$\text{Capacitor factor } f2 = \frac{\text{installed capacity of generator G2 (MVA)}}{\text{maximum capacity of G2 MVA (2400 MVA)}}$$

Source: Ref [2]

Influence of wind generation on dynamic stability

Generator 2: Synchronous generator





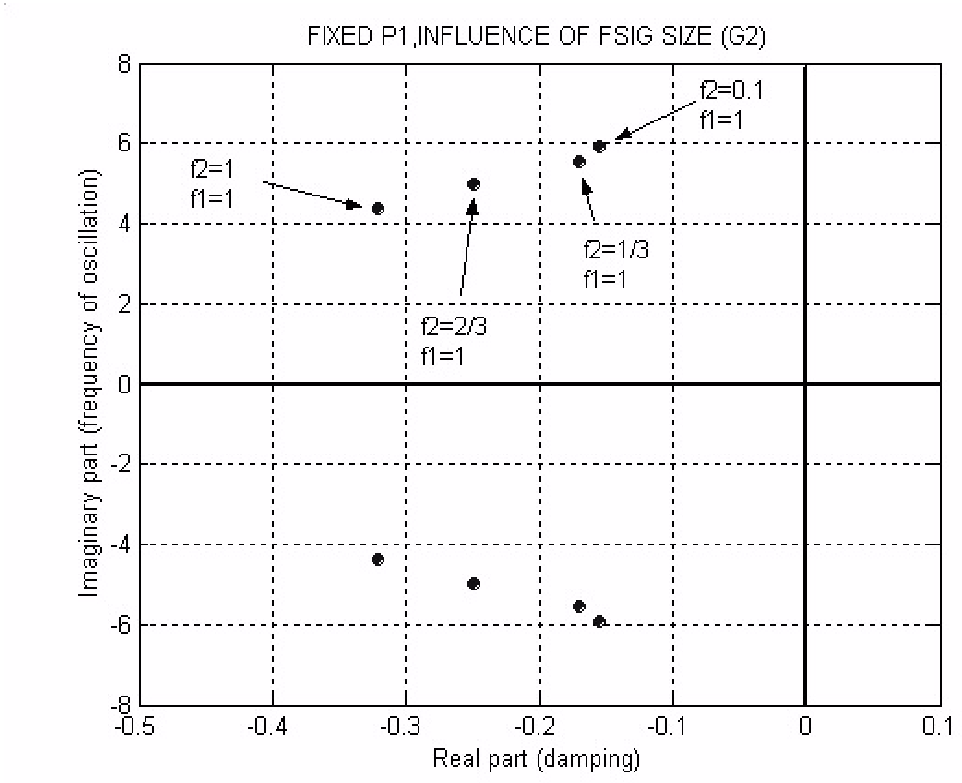
AVR Control | AVR + PSS Control

Variation of dominant eigenvalue loci with generation capacity

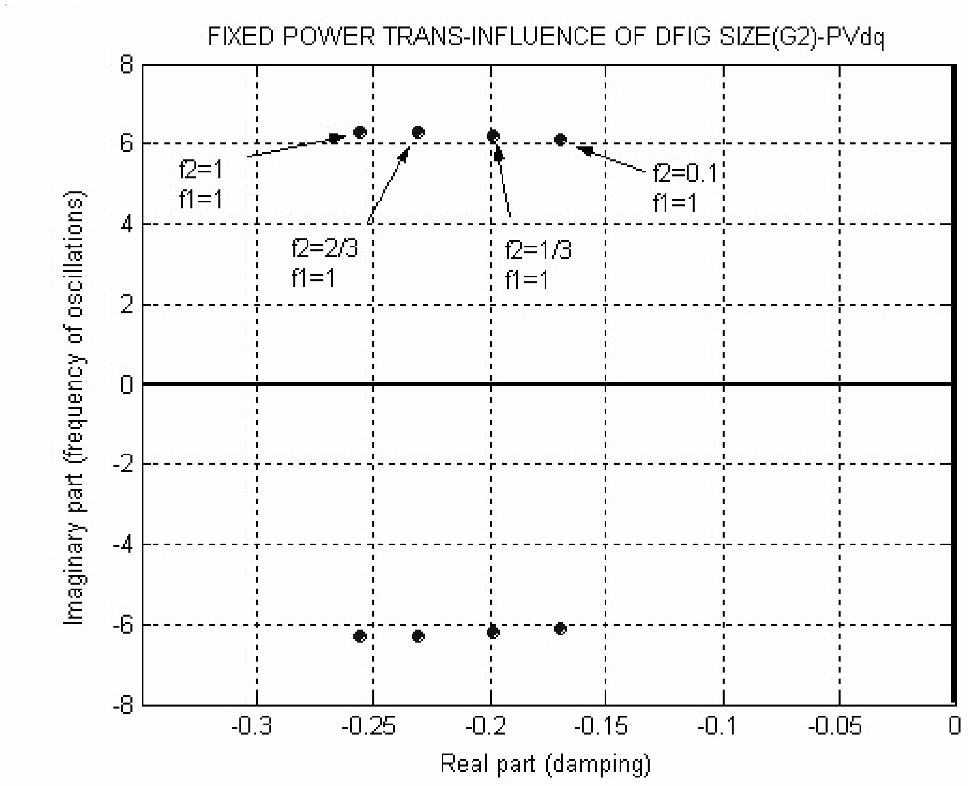
Source: Ref [2]

Influence of wind generation on dynamic stability

Generator 2: Wind generation



FSIG-wind farm



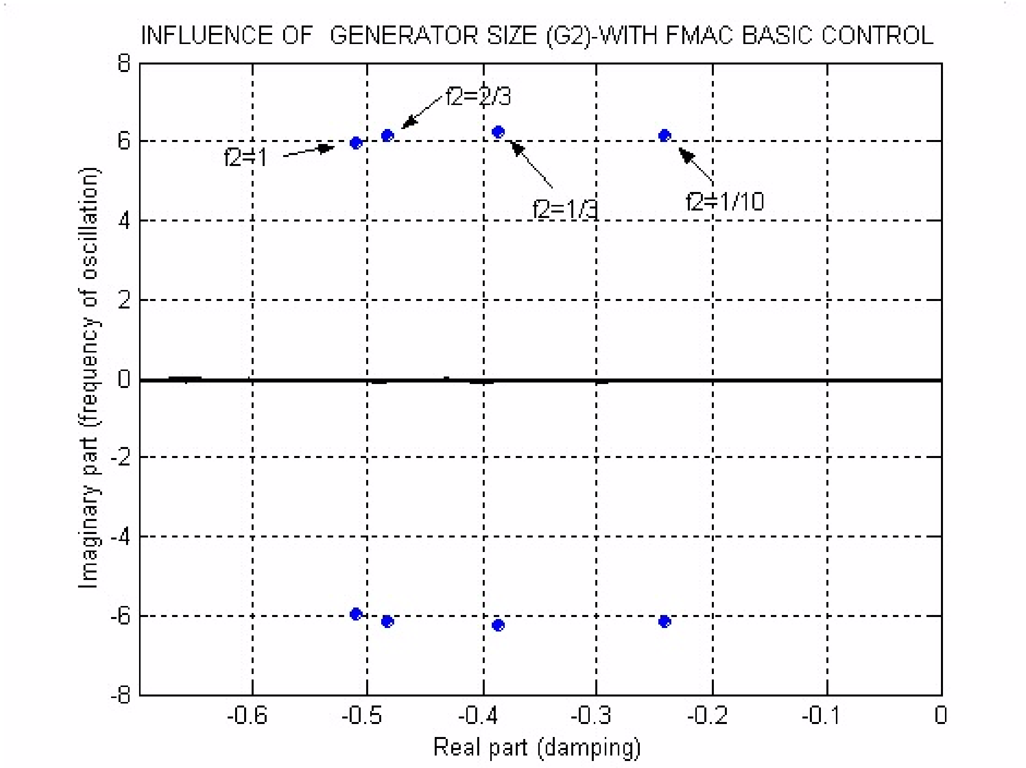
DFIG wind farm with current-mode control

Variation of dominant eigenvalue loci with generation capacity

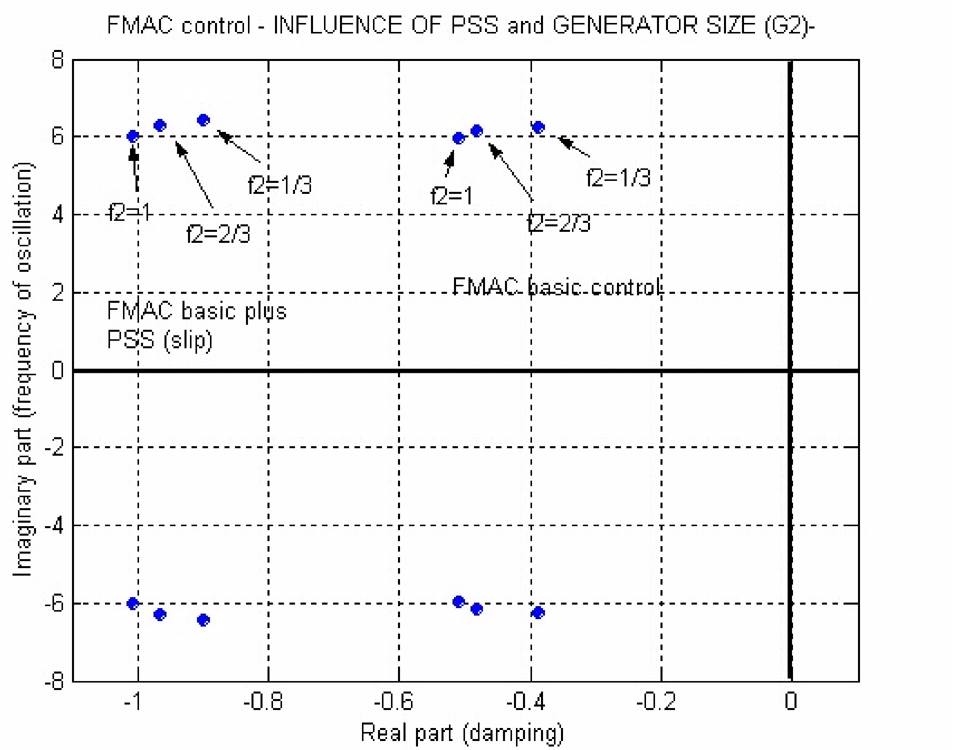
Source: Ref [2]

Influence of wind generation on dynamic stability

Generator 2: DFIG wind farm with FMAC control



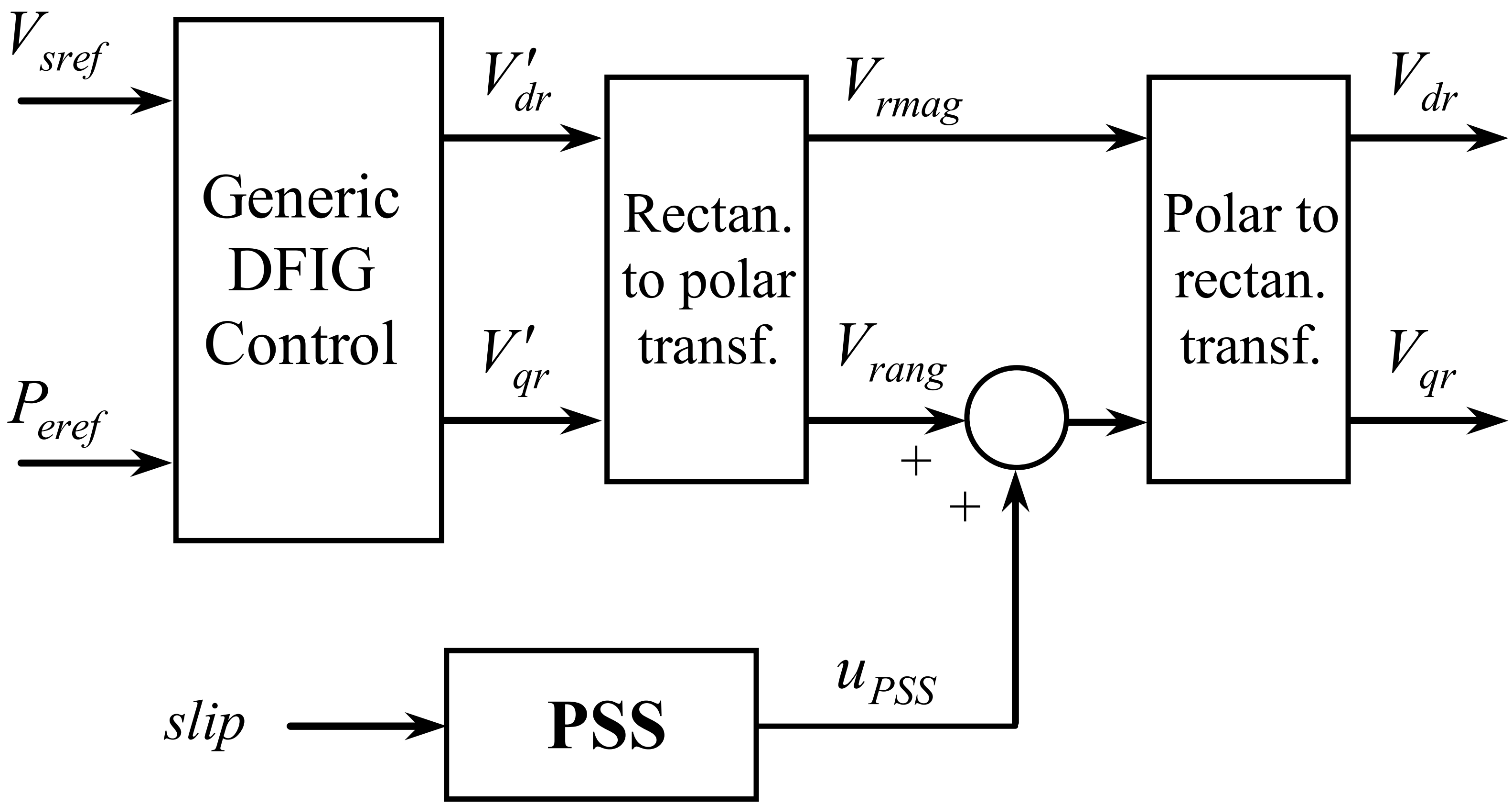
FMAC basic



FMAC basic + PSS control

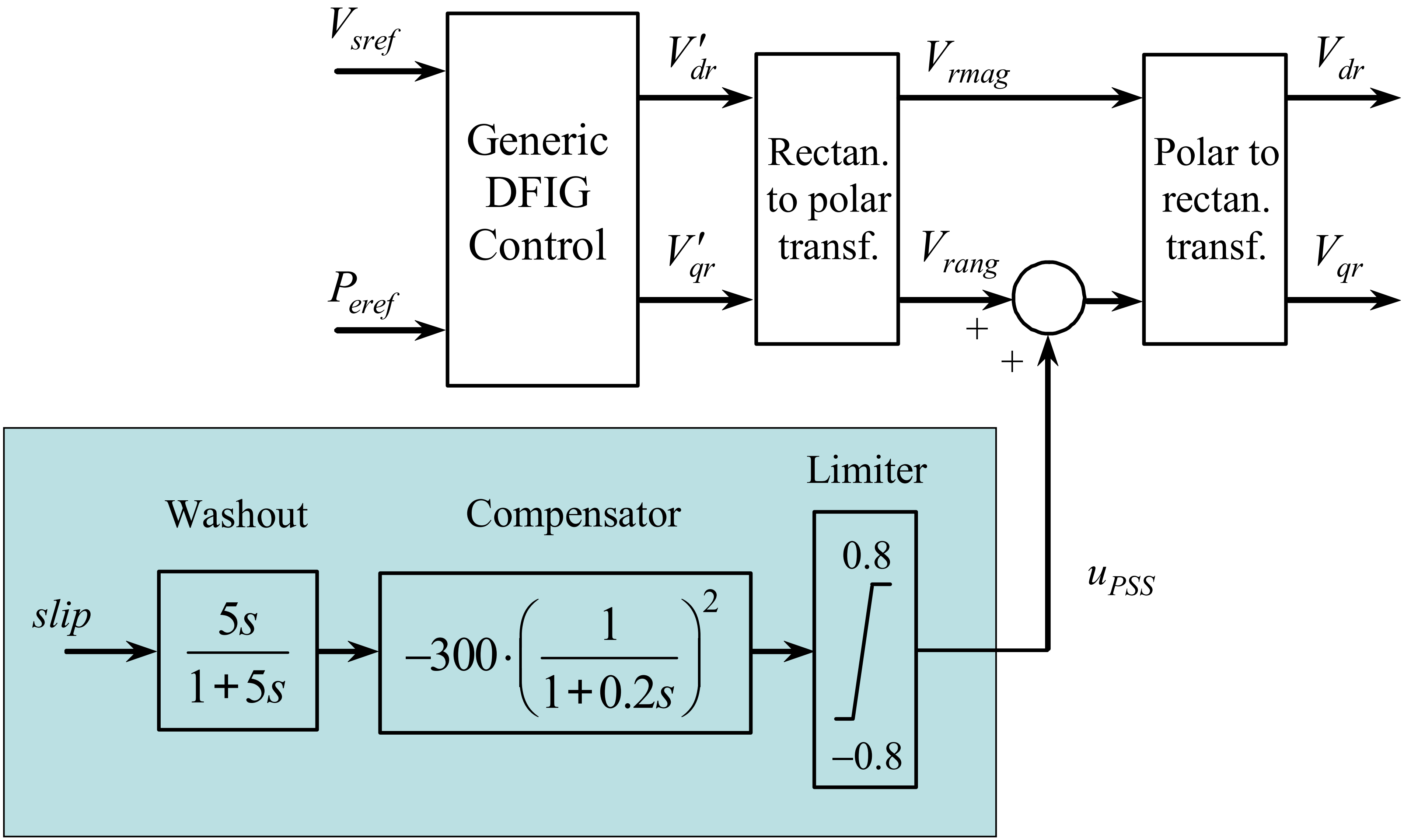
Variation of dominant eigenvalue loci with generation capacity

PSS for a generic DFIG controller



Source: Ref [5]

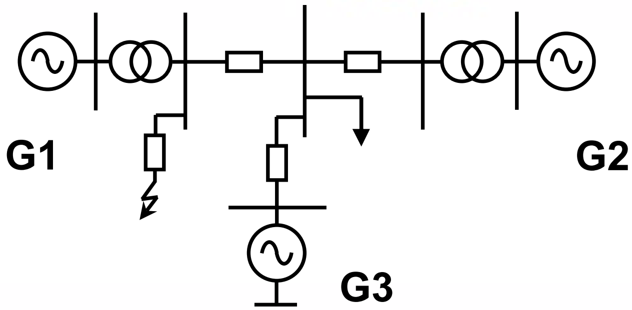
DFIG Power System Stabiliser

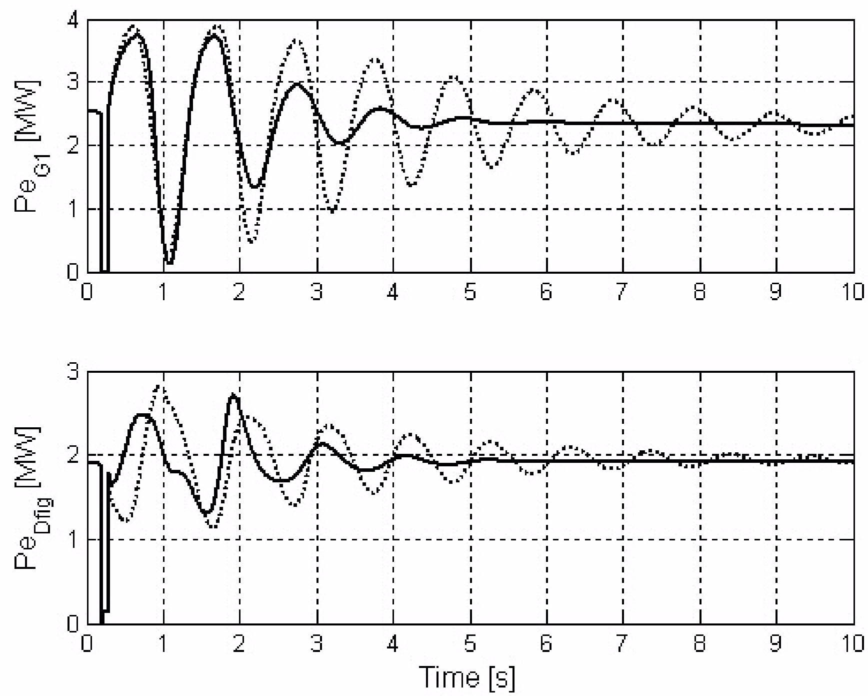


Source: Ref [5]

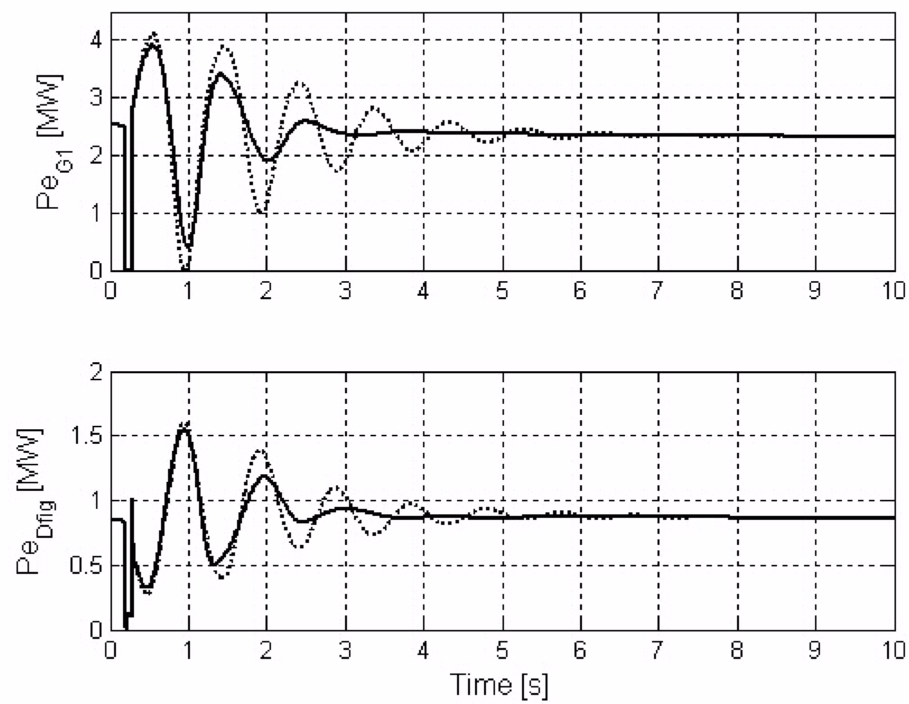
Control performance (transient stability)

Generator 1 (G1): Synchronous generator
Generator 2 (G2): DFIG





DFIG in super synchronous Operation (slip = -0.2)



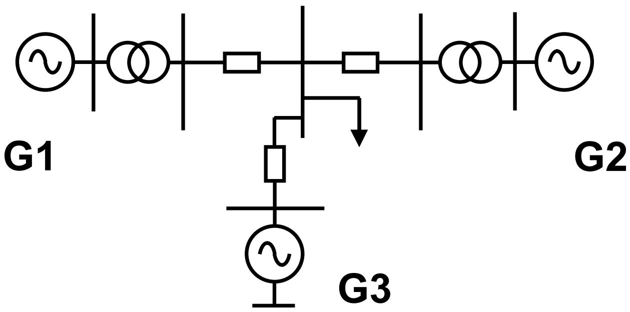
DFIG in sub synchronous Operation (slip = 0.2)

Fault applied at t=0.2 s with a clearance time of 150ms. (Full line: DFIG with PSS; dotted line: DFIG without PSS)

Source: Ref [5]

Control performance (dynamic stability)

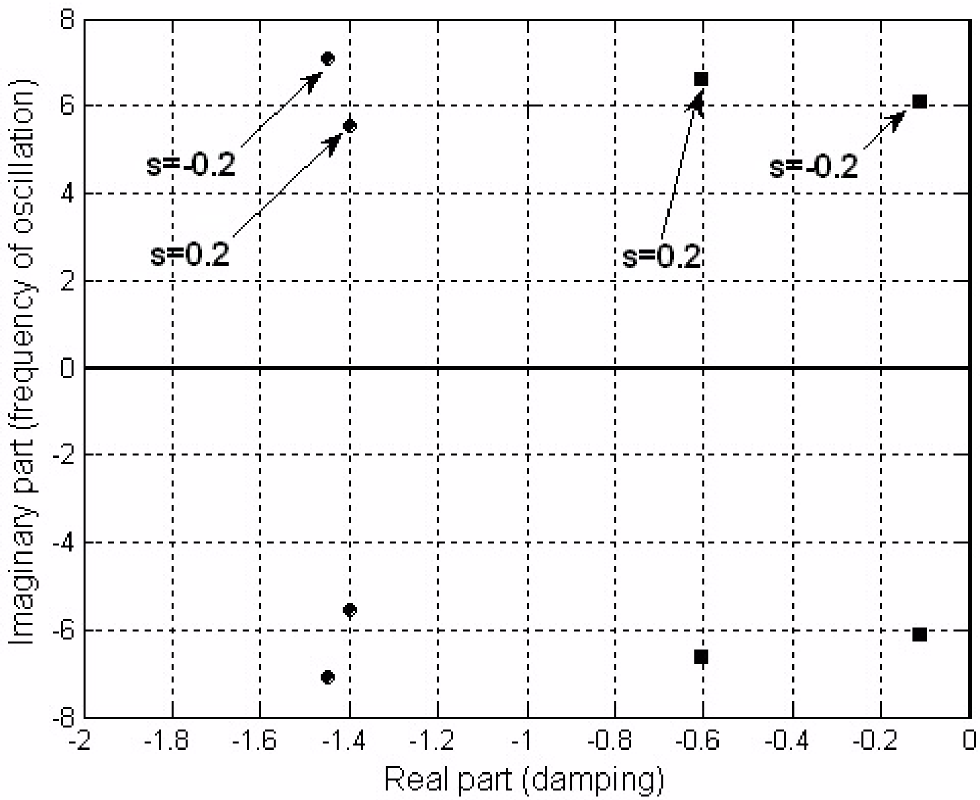
Generator 1 (G1): Synchronous generator
Generator 2 (G2): DFIG



Influence of PSS loop on the dominant eigenvalue for sub synchronous (s=0.2) and super synchronous operation (s=-0.2).
(With PSS •; without PSS ▪)

Operating situations

Slip	DFIG Stator power MW	Converter power MW	Total power Output MW
-0.2	1,928	375	2,303
0.2	857	-182	675



Source: Ref [5]

Reference for further reading

1. P. Kundur: "Power systems stability and control," McGraw-Hill, 1994.
2. O. Anaya-Lara, F. M. Hughes, N. Jenkins, and G. Strbac, “Influence of wind farms on power system dynamic and transient stability,” Wind Engineering, Vol. 30, No. 2, pp. 107-127, March 2006.
3. F. M. Hughes, O. Anaya-Lara, N. Jenkins, and G. Strbac, “Control of DFIG-based wind generation for power network support,” IEEE Transactions on Power Systems, Vol. 20, No. 4, pp. 1958-1966, November 2005.
4. O. Anaya-Lara, F. M. Hughes, N. Jenkins, and G. Strbac, “Rotor flux magnitude and angle control strategy for doubly fed induction generators,” Wind Energy, Vol. 9. No. 5, pp. 479-495, June 2006.
5. O. Anaya-Lara, F. M. Hughes, N. Jenkins, and G. Strbac, “Power system stabiliser for a generic DFIG-based wind farm controller,” paper accepted for publication at the IEE AC/DC Conference, March, 2006

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