Control of Distributed Generation

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Protection and Control of Distributed Energy Resources

Chapter 4

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Choose yourself and new technologies

HUMAN CAPITAL
HUMAN – BEST INVESTMENT!
Wrocław University of Technology
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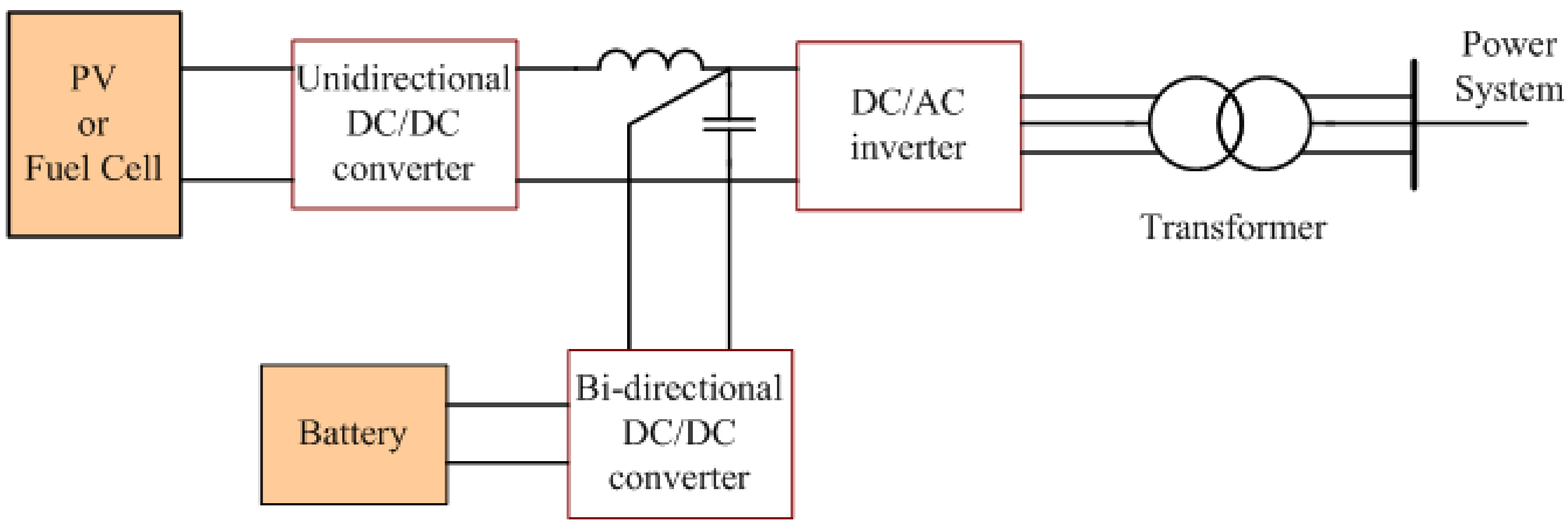
General Considerations

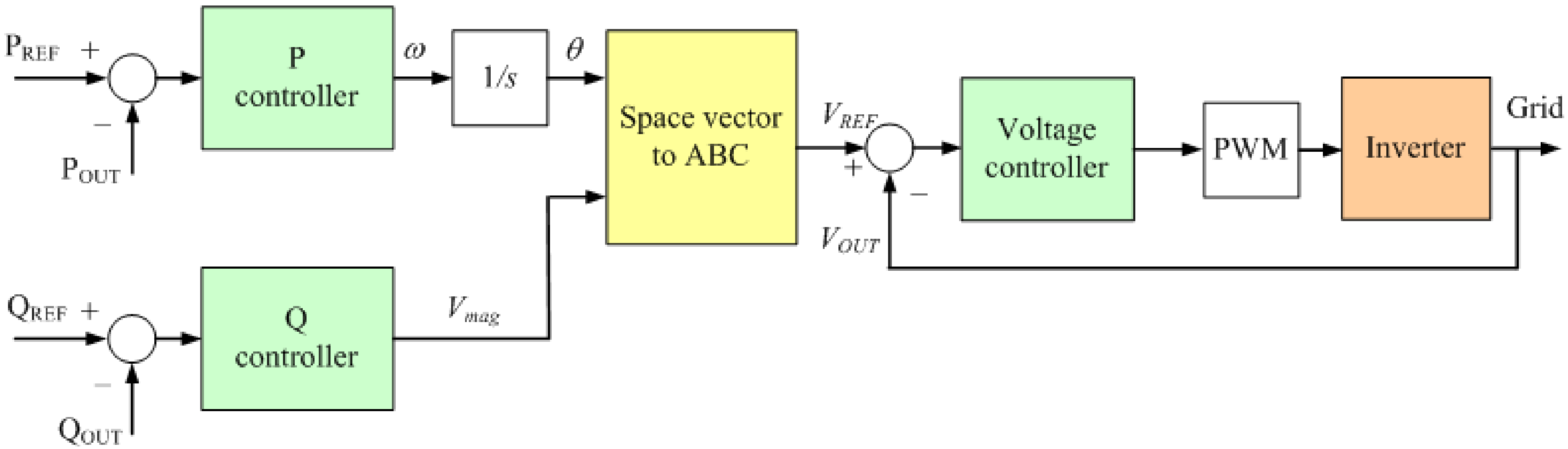
- From the economical point of view, optimal control maximizes the financial return on DG system investment.
- The fundamental goal of the control scheme is to determine whether or not the on-site generation should be operating during a particular hour.
- Buyback priority is used in cases where the operator wishes to produce electricity and sell any or all of the produced power back to the utility.

DC cources interconnetion to the Grid



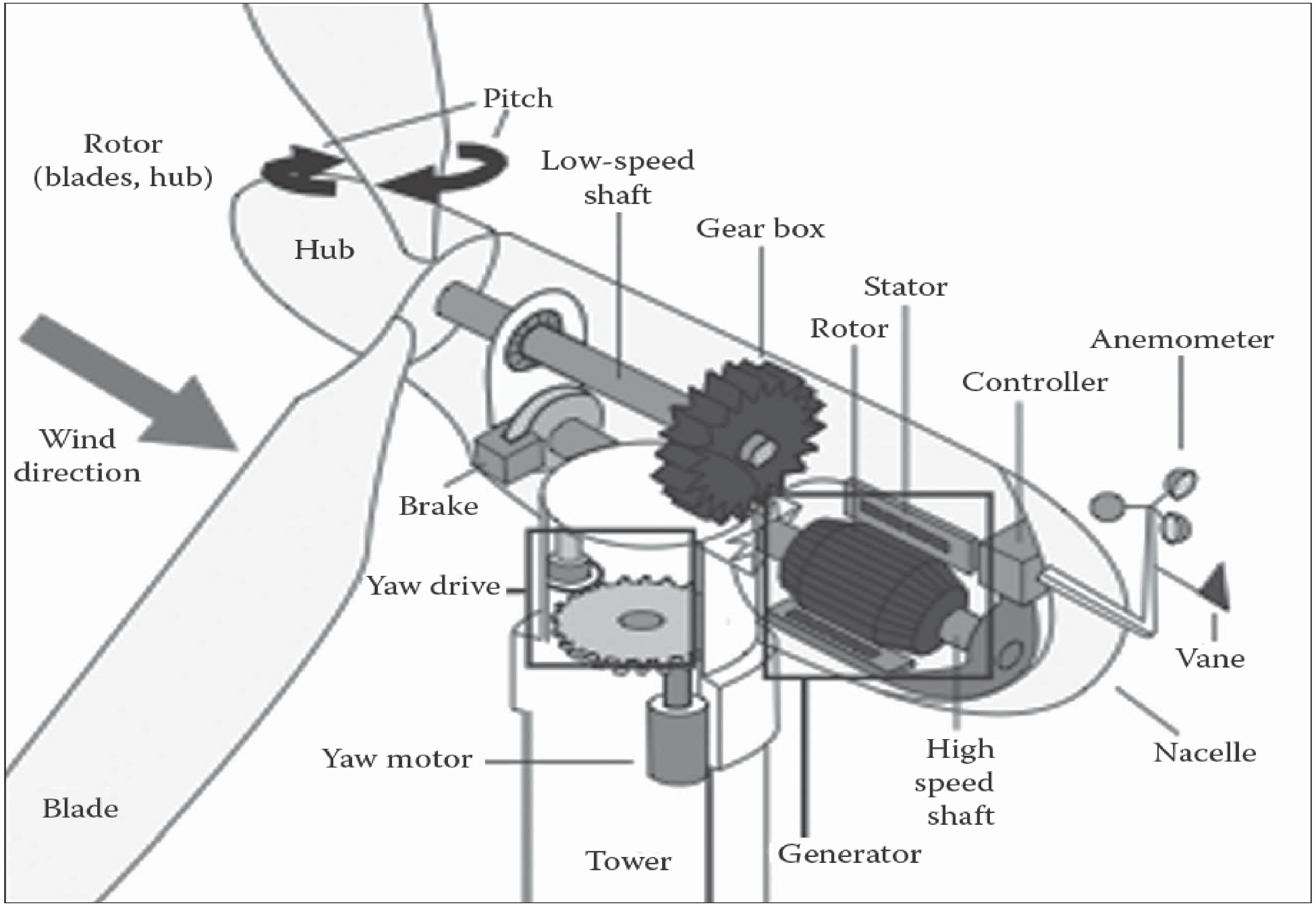
A PV or Fuel Cell grid-connected DG system with energy storage

Control of DC sources interconnetion to the Grid



Grid-connected power flow control scheme through output voltage regulation

Wind Turbine Structure



Nelson V., Wind Energy. CRC Press, 2009

Turbine Regulation

Pitch controller objectives:

- **to regulate aerodynamic torque in above-rated wind speeds;**
- **to minimize peaks in gearbox torque;**
- **to avoid excessive pitch activity;**
- **to minimize tower base loads as far as possible by controlling tower vibration, and**
- **to avoid exacerbating hub and blade root loads.**

Turbine Characteristics

The power transferred by the turbine blades is given by:

$$P_m = \frac{1}{2}\rho \cdot A_r \cdot C_p \cdot V_w^3$$

where:

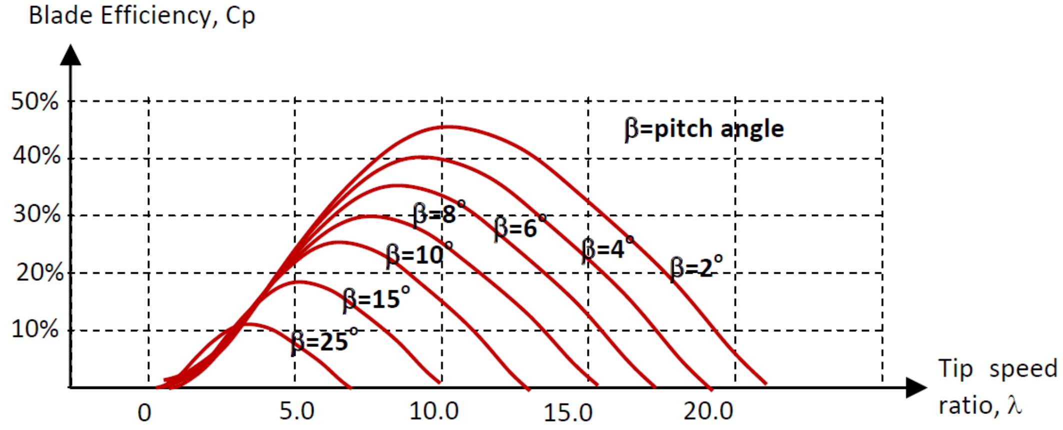
ρ – **air density;**

A_r – **area swept by the rotor;**

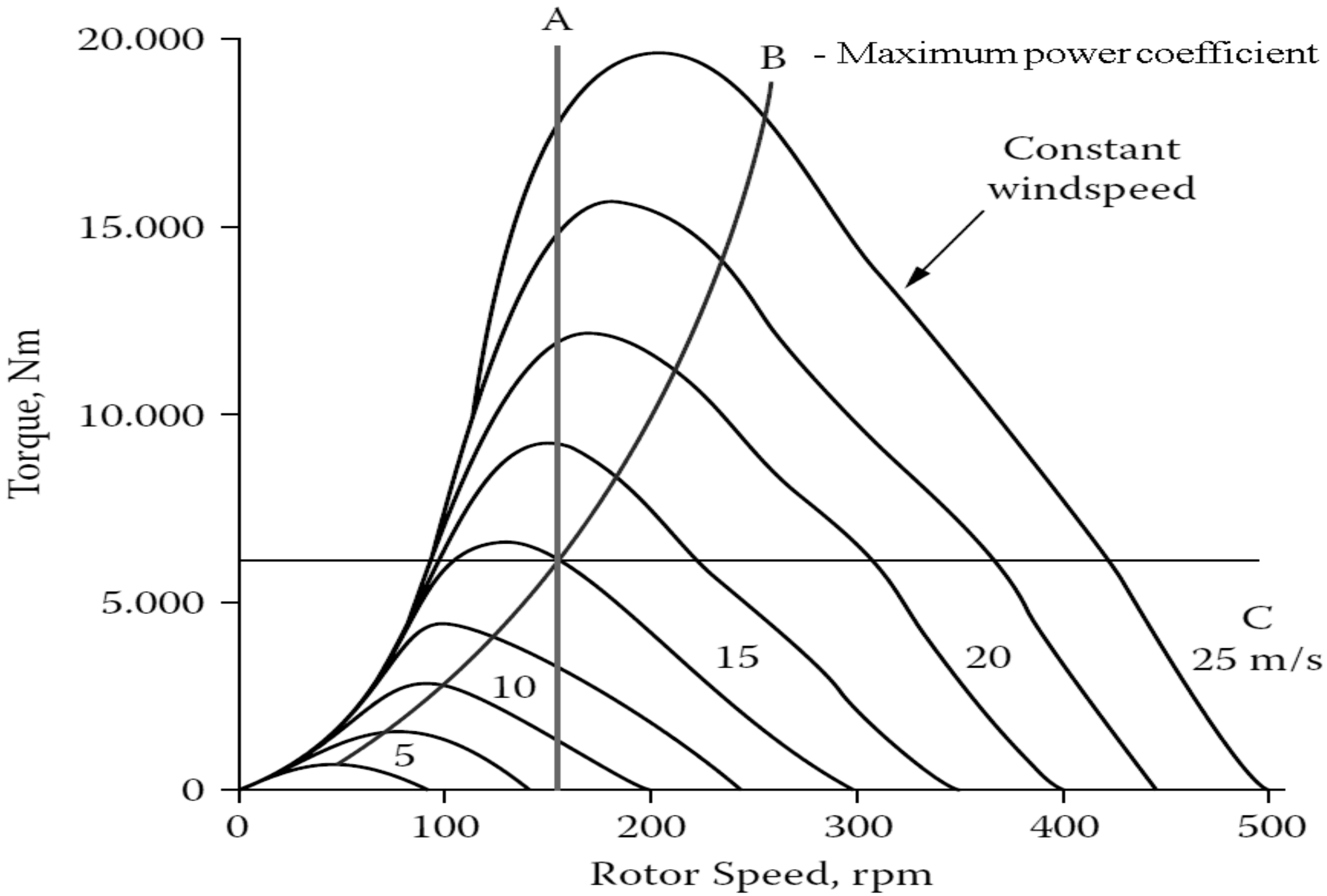
V_w – **wind velocity;**

C_p – **power coefficient;**

β – **pitch angle.**



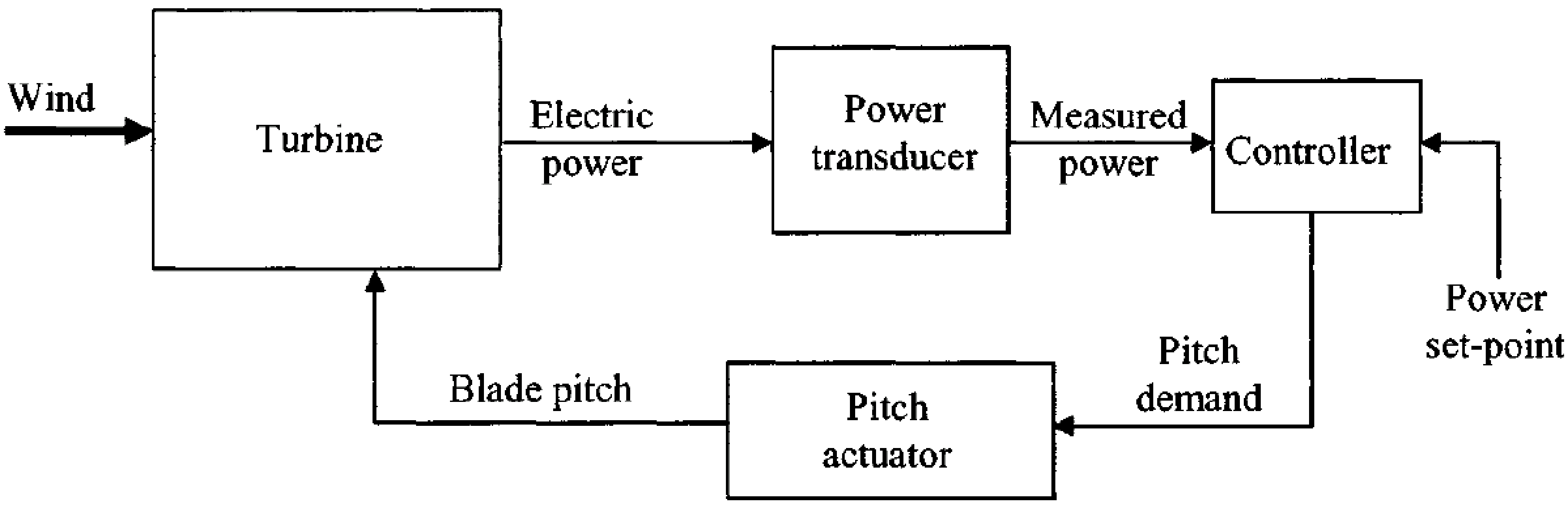
Theoretical curves of torque versus rpm for different wind speeds



Wind Turbine Control

- A pitch control system is one method to control rpm, start up (need high torque), and overspeed.
- The pitch can be changed to maintain a constant rpm for synchronous generators. For an induction generator, variable-speed generator that operates over a range of rpm in the run position, over this range the tip speed ratio is constant, and the unit operates at higher efficiency.
- Doubly fed induction generators have a large rpm range, around 50%, and are used because of the increased aerodynamic efficiency with blades in the run position for large wind turbines.

Main Control Loop for a Fixed-speed Pitch-regulated Turbine



Connection of embedded wind generation

Consideration of whether a wind generation scheme may be connected to a distribution circuit is based on its impact on other users of the network. Similar considerations apply to the connection of any load.

The main parameters relevant to the connection of wind turbines:

- **Slow (or steady-state) voltage variations,**
- **Rapid voltage changes (leading to flicker),**
- **Waveform distortion (i.e., harmonics),**
- **Voltage unbalance (i.e., negative phase sequence voltage), and**
- **Transient voltage variations (i.e., dips and sags).**

Lightning Protection

Lightning is a significant potential hazard to wind turbines and that appropriate protection measures need to be taken. Some years ago, it was thought that as the blades of wind turbines are made from non-conducting material (i.e., glass or wood-epoxy) then it was not necessary to provide explicit protection for these types of blades.

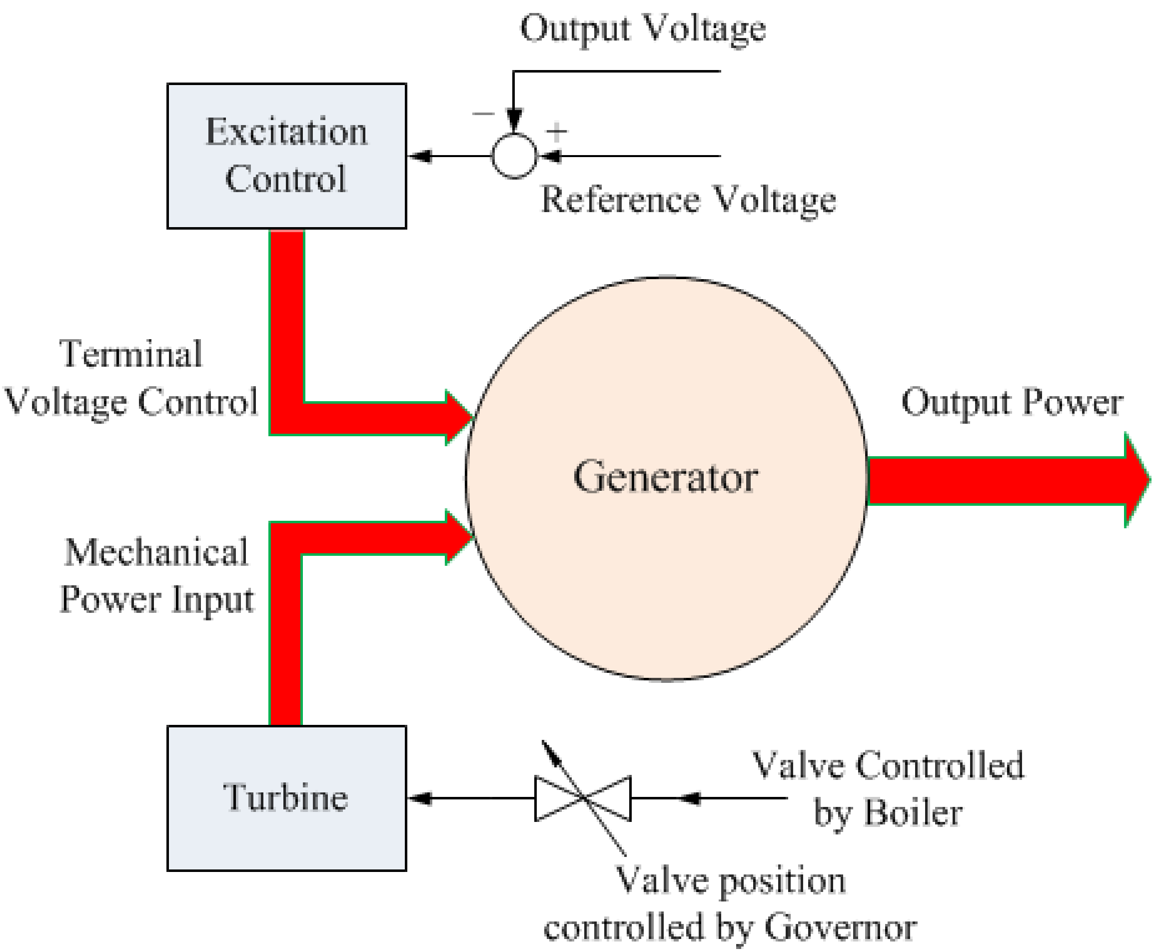
However, there is now a large body of site experience to show that lightning will attach to blades made from these materials and can cause catastrophic damage if suitable protection systems have not been fitted.

The main protective measures are good bonding, effective shielding and the use of appropriate surge protection devices at the zone boundaries.

Type of Rotating Generators

- **Fixed Speed Induction Generator (FSIG).**
- **Synchronous Generator (SG).**
- **Permanent Magnet Synchronous Generator (PMSG).**
- **Doubly-Fed Induction Generator (DFIG).**

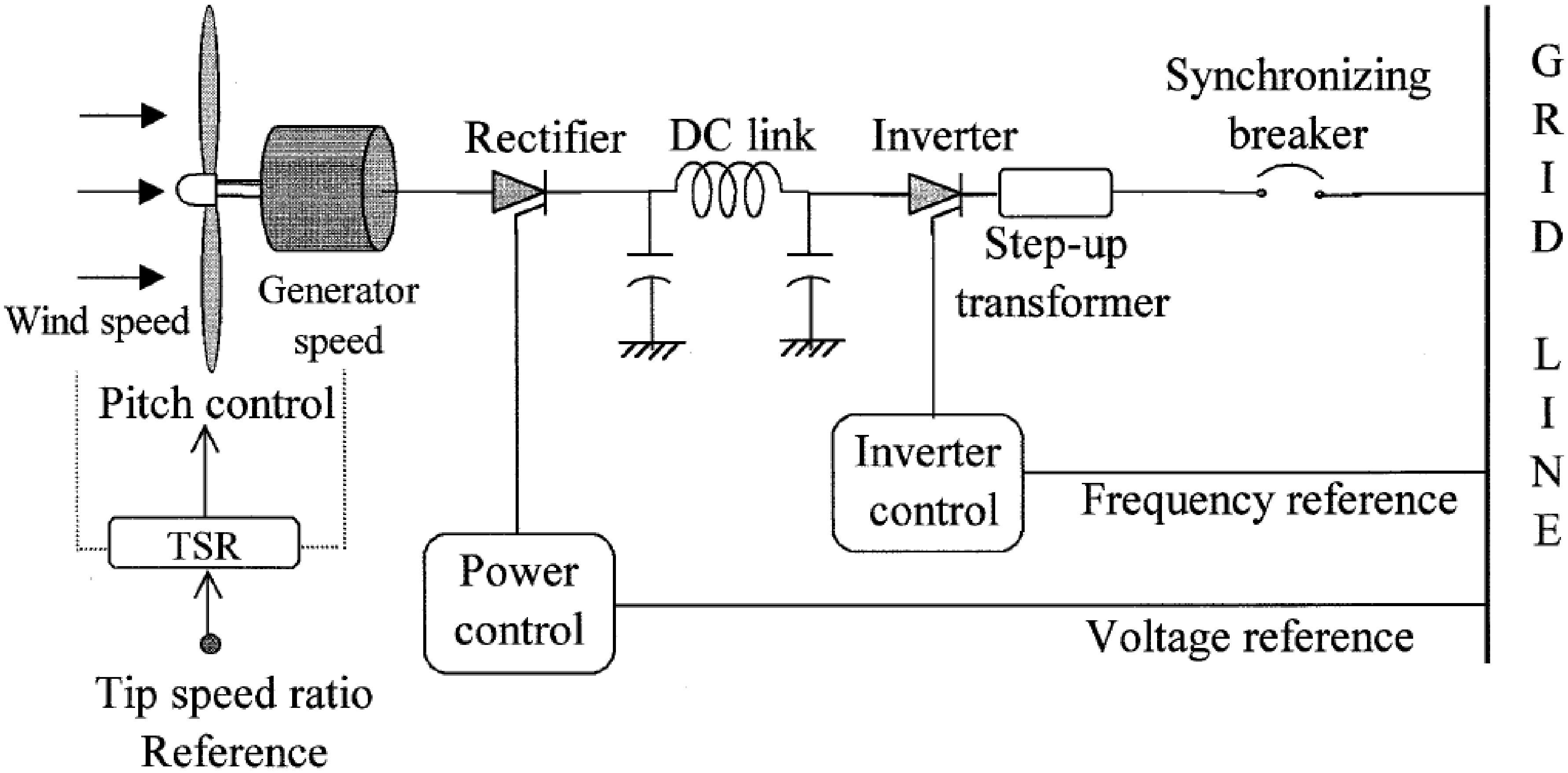
Generator as three terminal unit



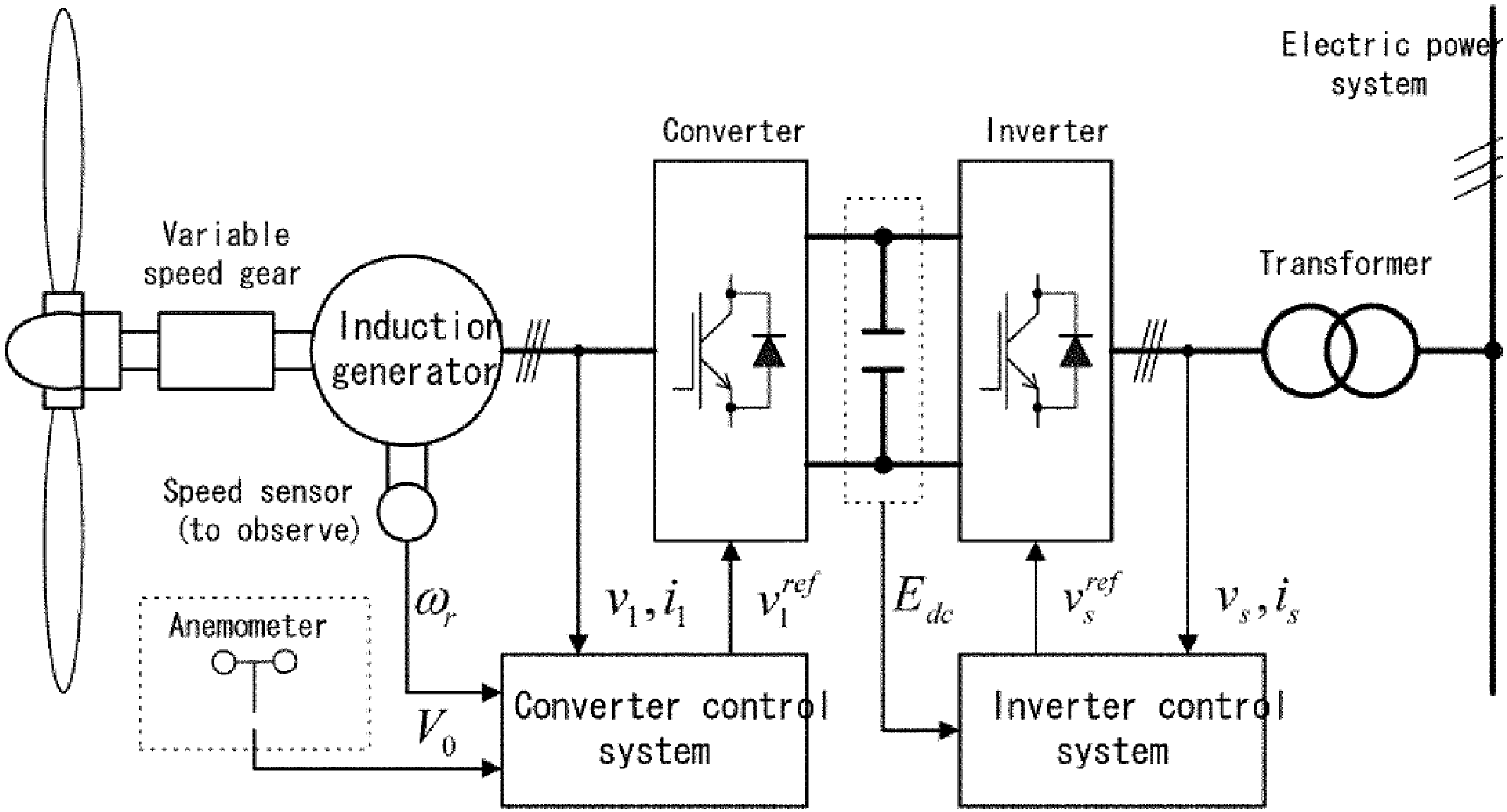
Turbine Regulation

- **DFIG wind turbines with converters rated at about 25–30% of the generator rating are becoming increasingly popular.**
- **These studies showed that DFIG-based wind turbines do not have an impact on oscillation, as it has modern power electronic devices to perform reactive power compensation and smoother grid connection besides speed control.**

Scheme of the grid-connected variable speed wind generator



Scheme of the grid-connected variable speed wind generator



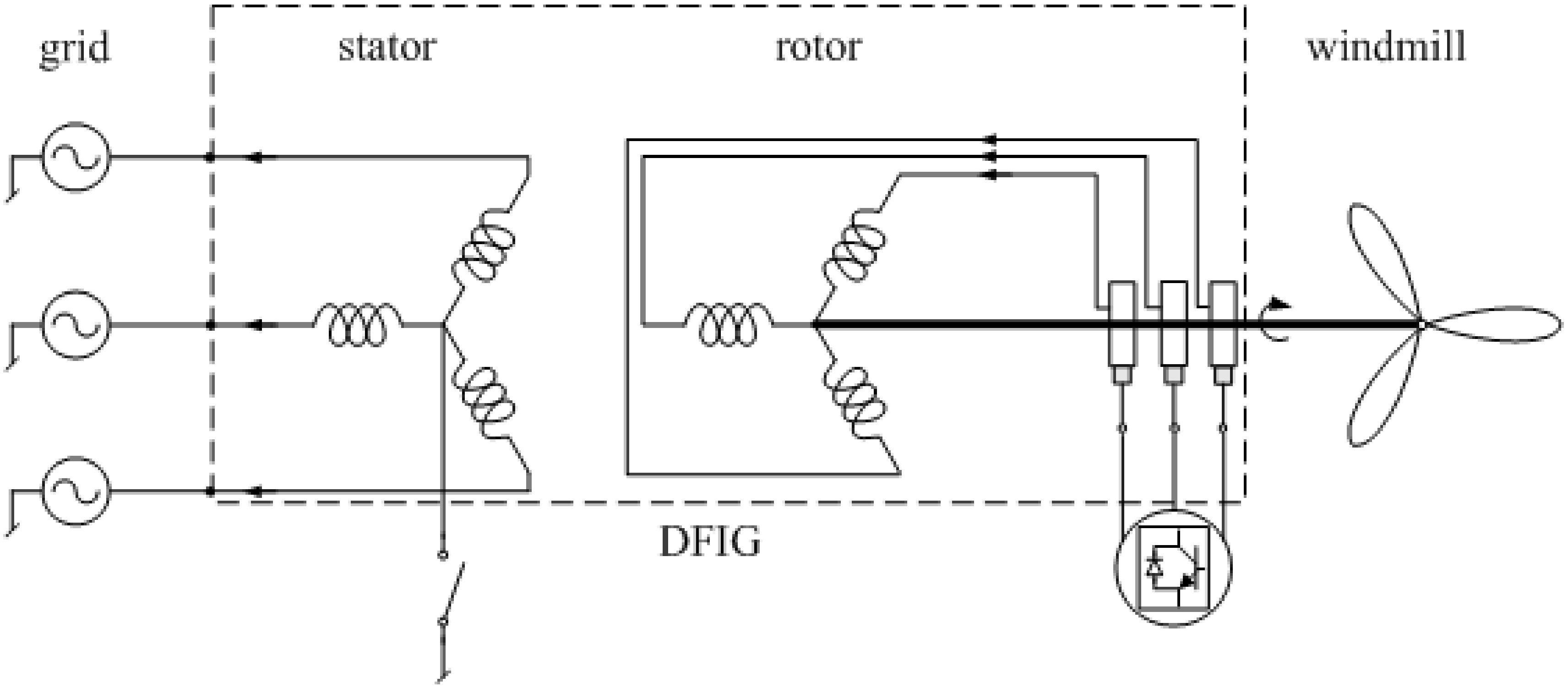
Doubly-Fed Induction Generator
DFIG/DFIM

- **DFIG-based wind turbines offer variable speed operation, four-quadrant active and reactive power capabilities, lower converter cost, and reduced power loss compared to wind turbines using fixed speed induction generators or fully-fed synchronous generators with full-sized converters.**

DFIG Model

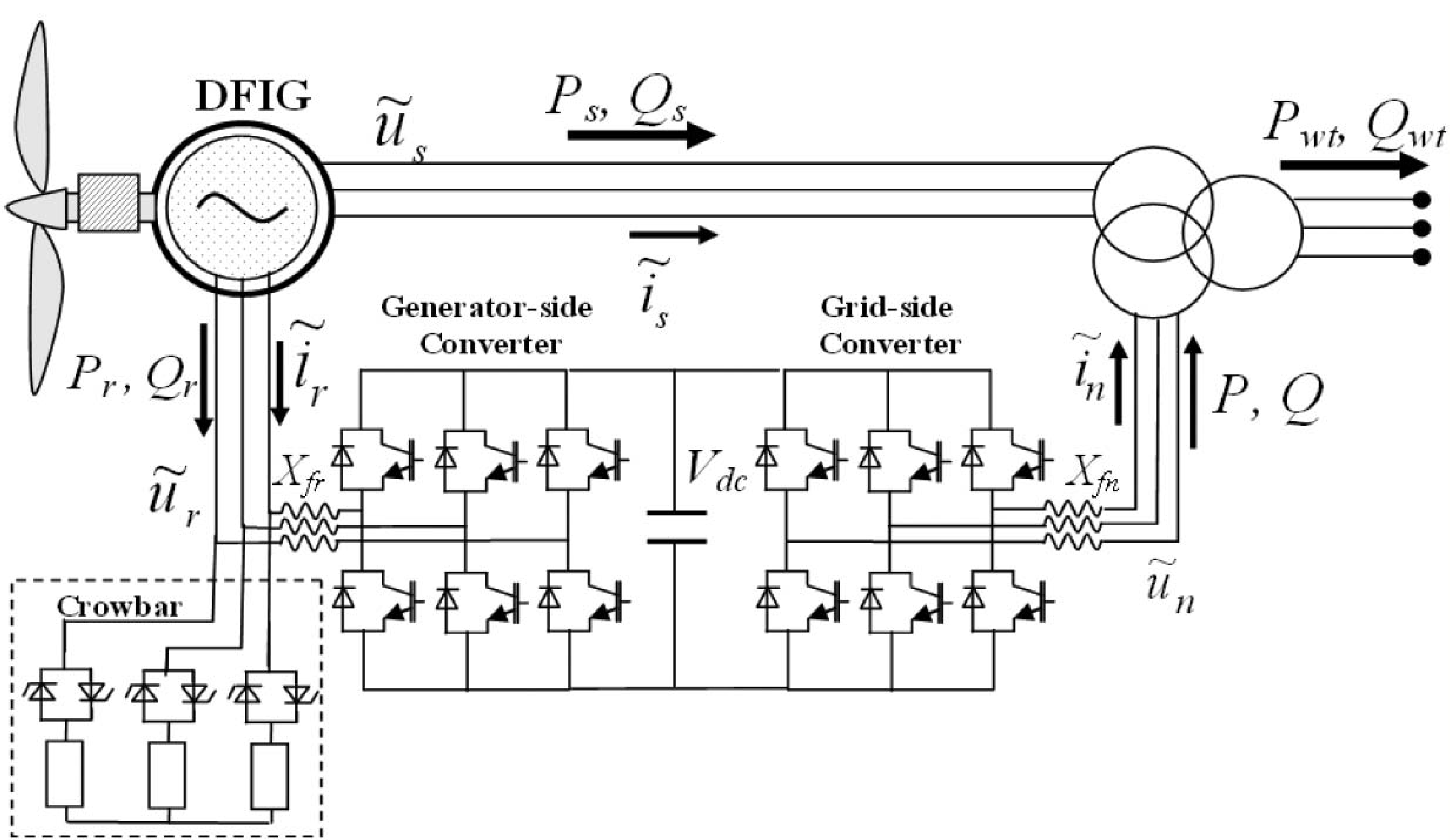
- **Recent interest in distributed generator installation into low voltage buses near electrical consumers, has created some new challenges for protection engineers that are different from traditional radially based protection methodologies.**
- **Therefore, typical protection configurations need to be re-thought such as re-closures, out-of-step monitoring, impedance relay protection zones with the detection of unplanned islanding of distributed generator systems.**

DFIG Model

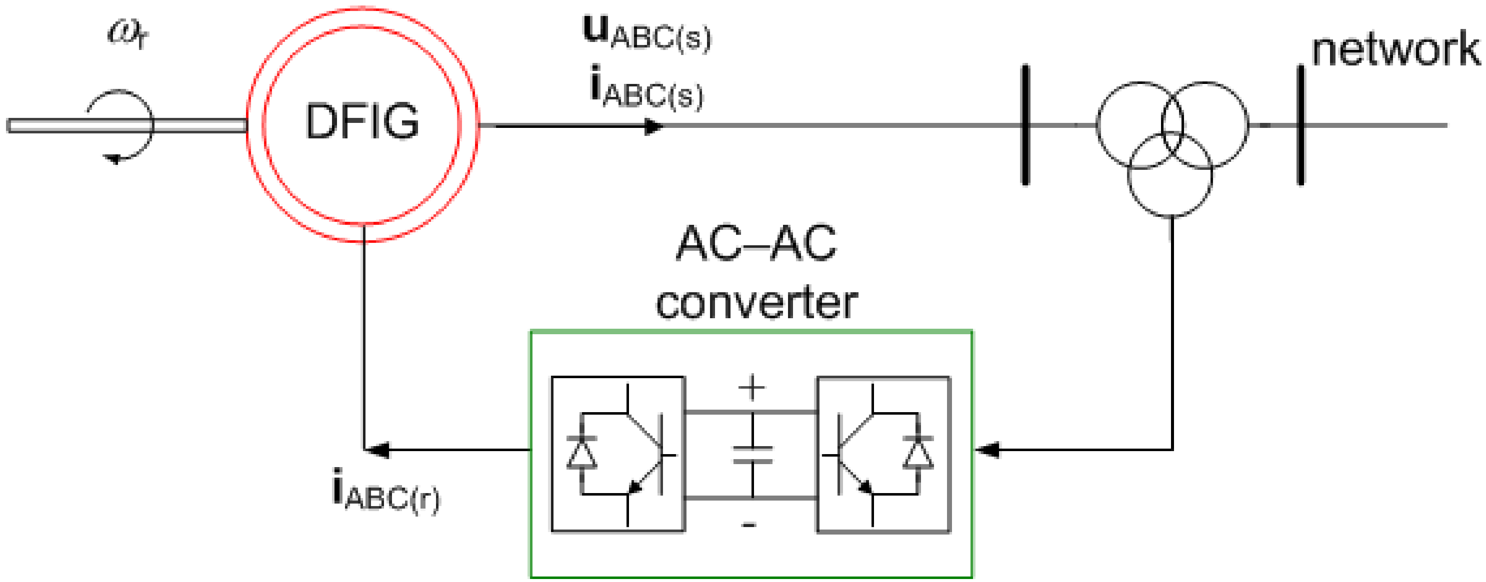


General structure of DFIG based Generator

DFIG Model


DFIG
$\tilde{u}_s$
P_s, Q_s
P_{wt}, Q_{wt}
$\tilde{i}_s$
Generator-side Converter
Grid-side Converter
P_r, Q_r
$\tilde{i}_r$
$\tilde{i}_n$
P, Q
X_{fr}
V_{dc}
X_{fn}
$\tilde{u}_r$
$\tilde{u}_n$
Crowbar

Available Measurements



$\mathbf{u}_{ABC(s)}$ – 3-phase stator voltage,
$\mathbf{i}_{ABC(s)}$ – 3-phase stator current,
$\mathbf{i}_{ABC(r)}$ – 3-phase stator current,
ω_r – rotor angular velocity.

Machine Coordinates System

3-phase stator coordinates:

$\mathbf{u}_{ABC(s)}$ – 3-phase stator voltage
$\mathbf{i}_{ABC(s)}$ – 3-phase stator current

$\alpha\beta0$ stator coordinates:

$\mathbf{i}_{\alpha\beta0}$ – $\alpha\beta0$ stator current
$\mathbf{u}_{\alpha\beta0}$ – $\alpha\beta0$ stator voltage

dq0 rotor coordinates:

$\mathbf{i}_{dq0}$ – dq0 rotor current
$\mathbf{u}_{dq0}$ – dq0 rotor voltage

3-phase rotor coordinates:

$\mathbf{u}_{ABC(r)}$ – 3-phase rotor voltage
$\mathbf{i}_{ABC(r)}$ – 3-phase rotor current

xy stator flux oriented coordinates:

$\mathbf{i}_{xy(s)}$, $\mathbf{i}_{xy(r)}$ – xy stator or rotor currents
$\mathbf{u}_{xy(s)}$, $\mathbf{u}_{xy(r)}$ – xy stator or rotor voltages

Machine Coordinates System

Basic transformations:

$$\mathbf{x}_{\alpha\beta 0} = \mathbf{C}^{-1}\mathbf{x}_{ABC}$$

$$\mathbf{x}_{ABC} = \mathbf{C}\mathbf{x}_{\alpha\beta 0}$$

where:

$$\mathbf{C} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ 1 & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \qquad \mathbf{C}^{-1} = \frac{2}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}$$

Zero-sequence component may be omitted, then:

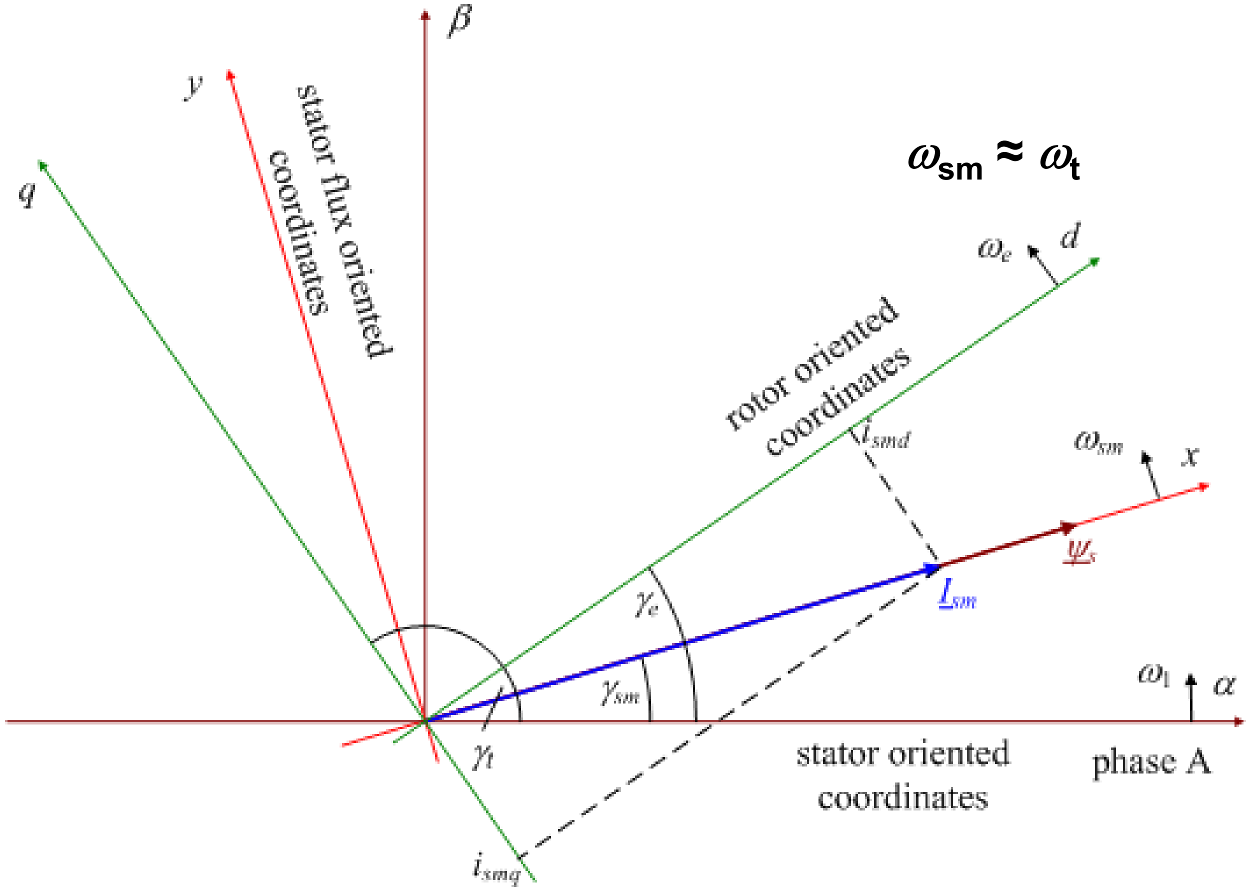
$\underline{x}_{\alpha\beta} = x_\alpha + \mathrm{j}x_\beta$ **for voltage, current or flux, stator reference.**

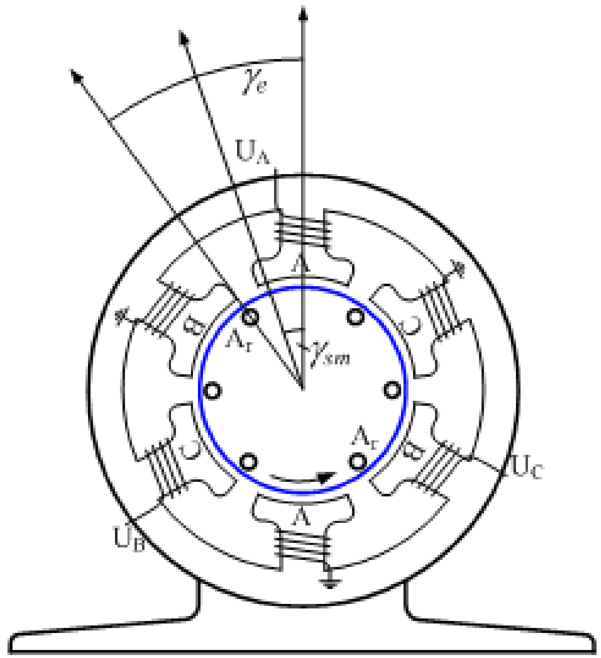
$\underline{x}_{dq} = \underline{x}_{\alpha\beta}\mathrm{e}^{\mathrm{j}\gamma_e}$ **for voltage, current or flux, rotor reference.**

$\underline{x}_{xy(s)} = \underline{x}_{\alpha\beta}\mathrm{e}^{-\mathrm{j}\gamma_{sm}} = x_{sx} + \mathrm{j}x_{sy}$ **for stator voltage, current or flux, stator flux reference.**

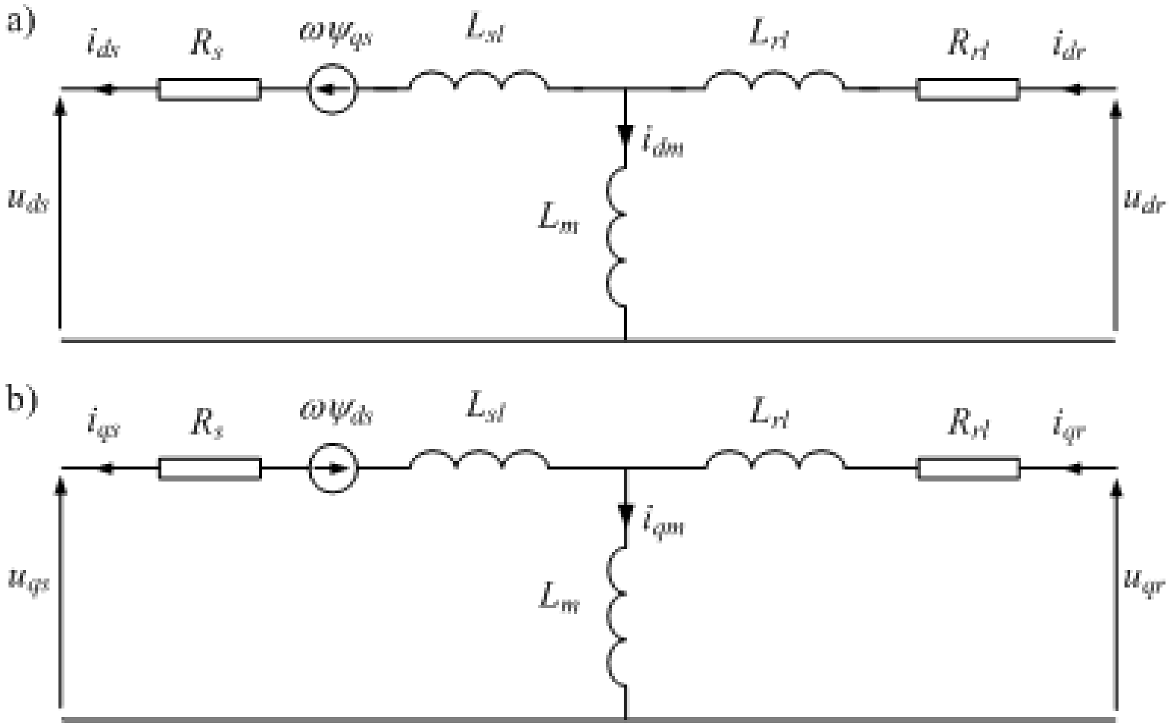
$\underline{x}_{xy(r)} = \underline{x}_{dq}\mathrm{e}^{\mathrm{j}(\gamma_e - \gamma_{sm})} = x_{rx} + \mathrm{j}x_{ry}$ **for rotor voltage, current or flux, stator flux reference.**

Machine Coordinates System





DFIG – equivalent scheme in *dq* axis



$$\underline{u}_{dq(s)} = -R_s \underline{i}_{dq(s)} - R_r \underline{i}_{dq(r)} - L_{sl} \frac{\mathrm{d}}{\mathrm{d}t} \underline{i}_{dq(s)} - L_{rl} \frac{\mathrm{d}}{\mathrm{d}t} \underline{i}_{dq(r)} - \mathrm{j}\omega\left(L_s \underline{i}_{dq(s)} + L_m \underline{i}_{dq(r)}\right) + \underline{u}_{dq(r)}$$

Control Algorithm

- **DFIG control algorithm is based on the observation that active and reactive stator power: P_s, Q_s may be independently defined as the functions of rotor currents in xy – coordinates:**

$$P_s = \frac{2}{3}\left(u_{sx} i_{sx} + u_{sy} i_{sy}\right) \approx \frac{2L_s}{3L_m}\left|U_s\right| i_{ry}$$

$$Q_s = \frac{2}{3}\left(u_{sy} i_{sx} - u_{sx} i_{sy}\right) \approx \frac{2L_s}{3L_m}\left|U_s\right|\left(i_{rx} - \left|i_{sm}\right|\right)$$

- **In these equations rotor current components can be forced by changing the rotor voltage.**

Control Algorithm

The algorithm is as follows:

1. **Read the input measurements: $u_{ABC(s)}$, $i_{ABC(s)}$, $i_{ABC(r)}$ and transform its to $\alpha\beta$ coordinates.**
2. **Read the rotor velocity ω_r and calculate the instantaneous rotor angle and slip:**

$$\gamma_e = \int_0^t p\omega_r \mathrm{d}\tau + \gamma_{e0} \qquad \omega_{sl} = \omega_s - p\omega_r$$

3. **Calculate the rotor current in *dq* coordinates.**
4. **Calculated the magnetizing current in *xy* coordinates:**

$$i_{smd} = i_{rd} - \frac{L_s}{L_m} i_{s\alpha} \qquad I_{sm} = \sqrt{i_{smd}^2 + i_{smq}^2} \qquad \gamma_{sm} = \mathrm{arctg}\frac{i_{smq}}{i_{smd}}$$

$$i_{smq} = i_{rq} - \frac{L_s}{L_m} i_{s\beta}$$

Control Algorithm

5. **Calculate the current in *xy* coordinates:**

$$\mathbf{i}_{xy} = \mathbf{i}_{dq} e^{j\gamma_{sm}}$$

6. **Perform the PI algorithm for regulation of active and reactive power:**

$$\Delta P = P_{ref} - P$$

$$\Delta Q = Q_{ref} - Q$$

$$i_{rxref} = K_{P1}\Delta Q + K_{I1}\int_0^t \Delta Q \, d\tau + i_{rxref0}$$

$$i_{ryref} = K_{P1}\Delta P + K_{I1}\int_0^t \Delta P \, d\tau + i_{ryref0}$$

7. **Perform the PI algorithm for regulation of rotor voltage:**

$$\Delta i_{rx} = i_{rxref} - i_{rx}$$

$$\Delta i_{ry} = i_{ryref} - i_{ry}$$

$$u_{prx} = K_{P2}\Delta i_{rx} + K_{I2}\int_0^t \Delta i_{rx} \, d\tau + u_{prx0}$$

$$u_{pry} = K_{P2}\Delta i_{ry} + K_{I2}\int_0^t \Delta i_{ry} \, d\tau + u_{pry0}$$

Control Algorithm

8. Determine the rotor voltage in *xy* coordinates:

$$u_{rx} = u_{drx} + u_{prx}$$
$$u_{ry} = u_{dry} + u_{pry}$$

where:

$$u_{drx} = -\omega_{sl}\sigma L_r i_{ry}$$
$$u_{dry} = \omega_{sl}\sigma L_r\left(\sigma_1 I_{sm} - i_{rx}\right)$$

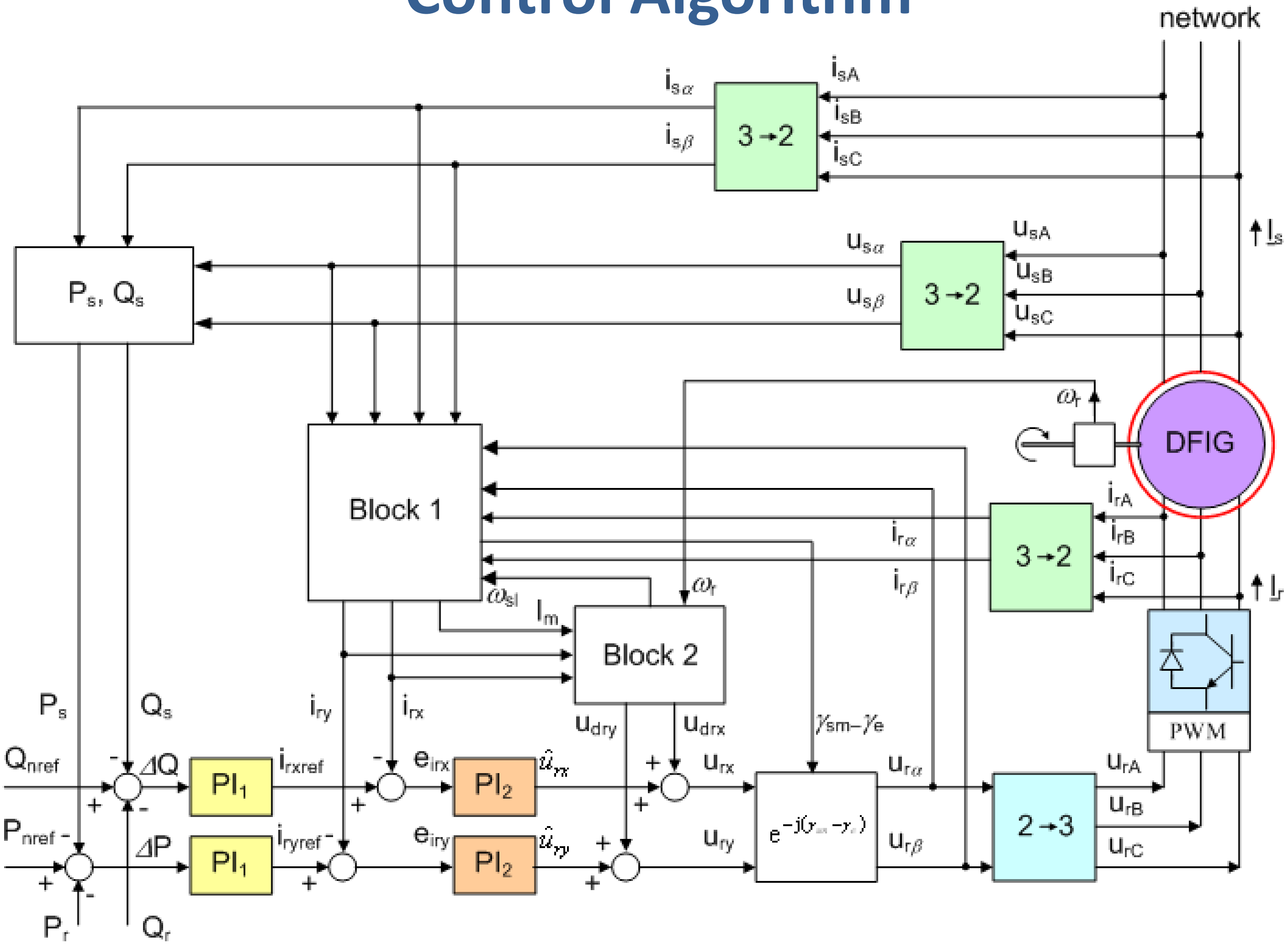
9. Determine the rotor voltage in 3-phase coordinates:

$$\underline{\mathbf{u}}_{\alpha\beta(r)} = \underline{\mathbf{u}}_{xy(r)} \mathrm{e}^{-\mathrm{j}\left(\gamma_{sm} - \gamma_e\right)}$$
$$\mathbf{u}_{ABC(r)} = \mathbf{C}\mathbf{u}_{\alpha\beta(r)}$$

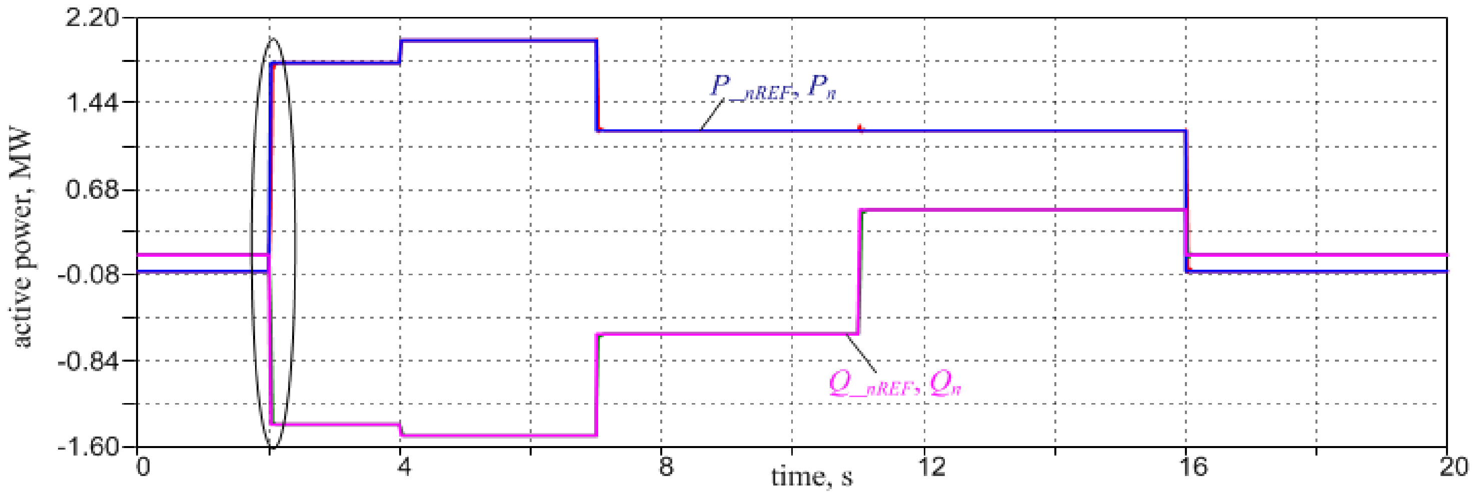
10. Apply for controlling the Electronic Converter:

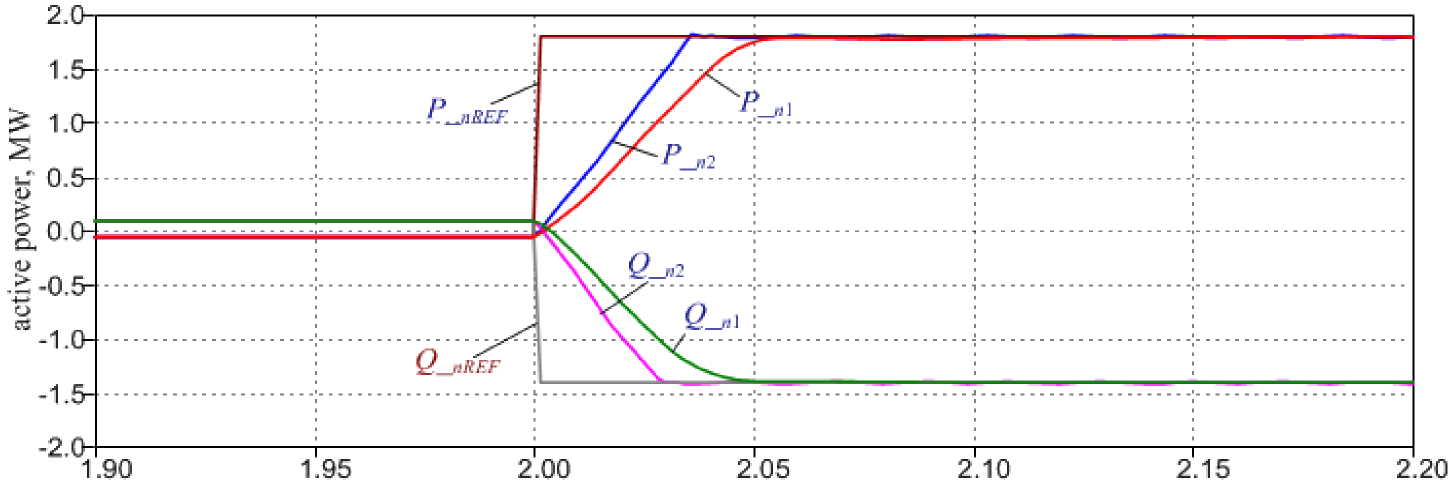
$$\mathbf{u}_{ABC(r)} \Rightarrow \mathrm{PWM}$$

Control Algorithm

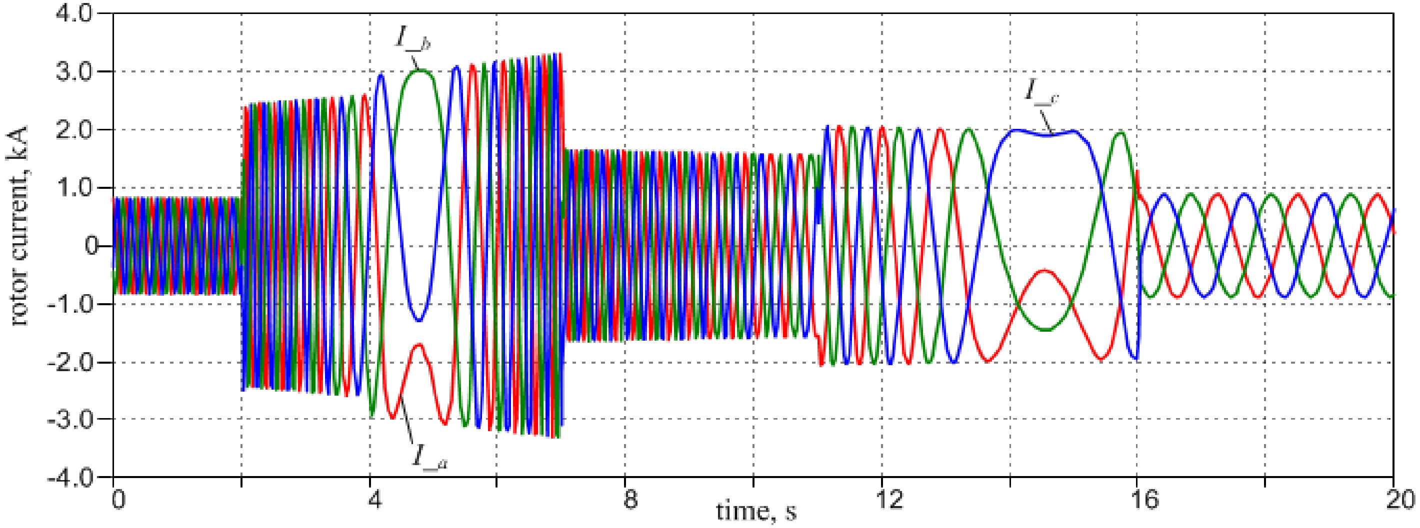


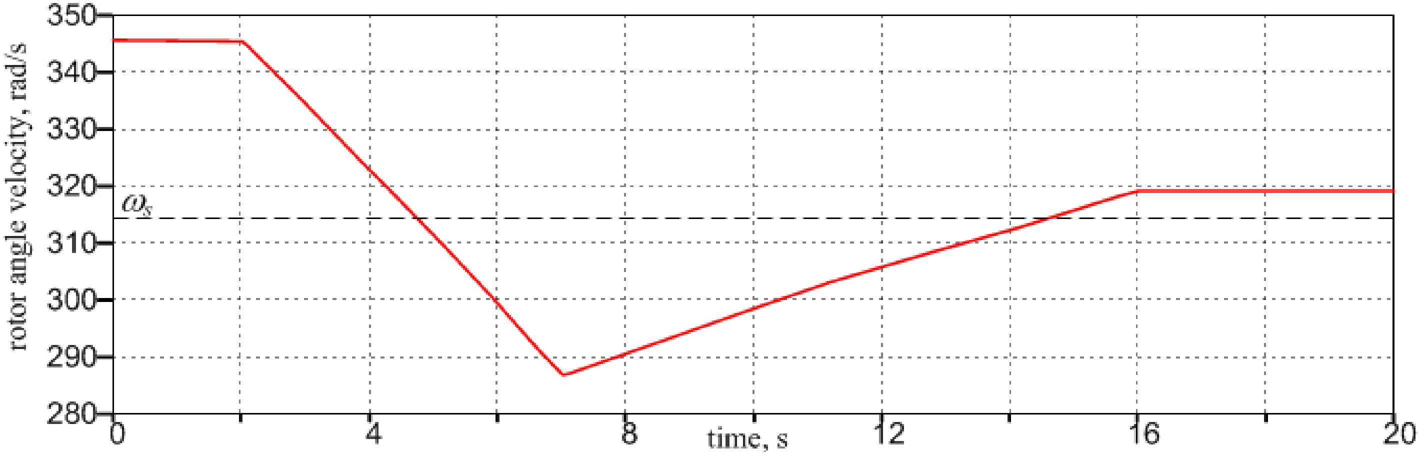
Control Algorithm



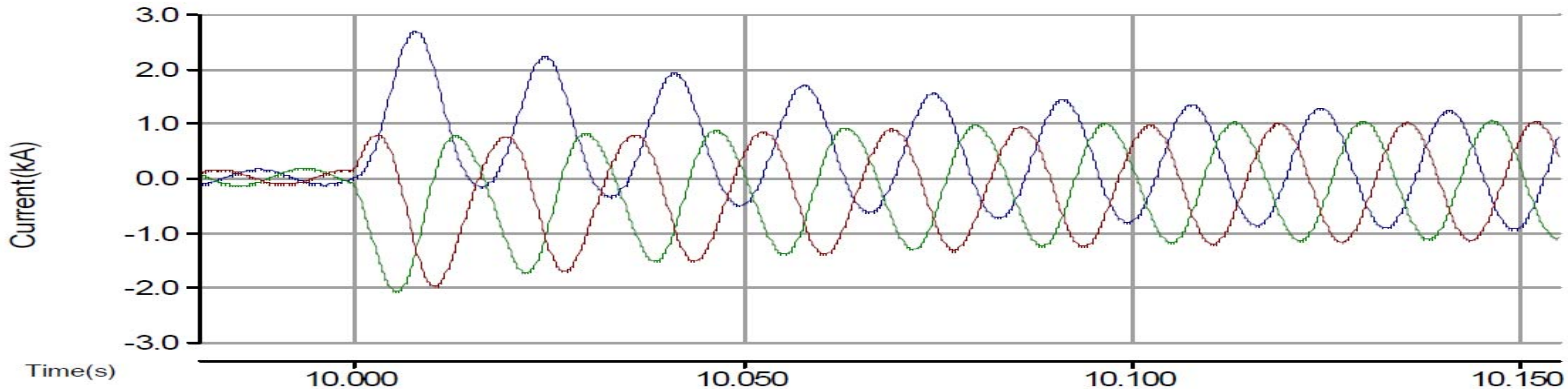


Control Algorithm

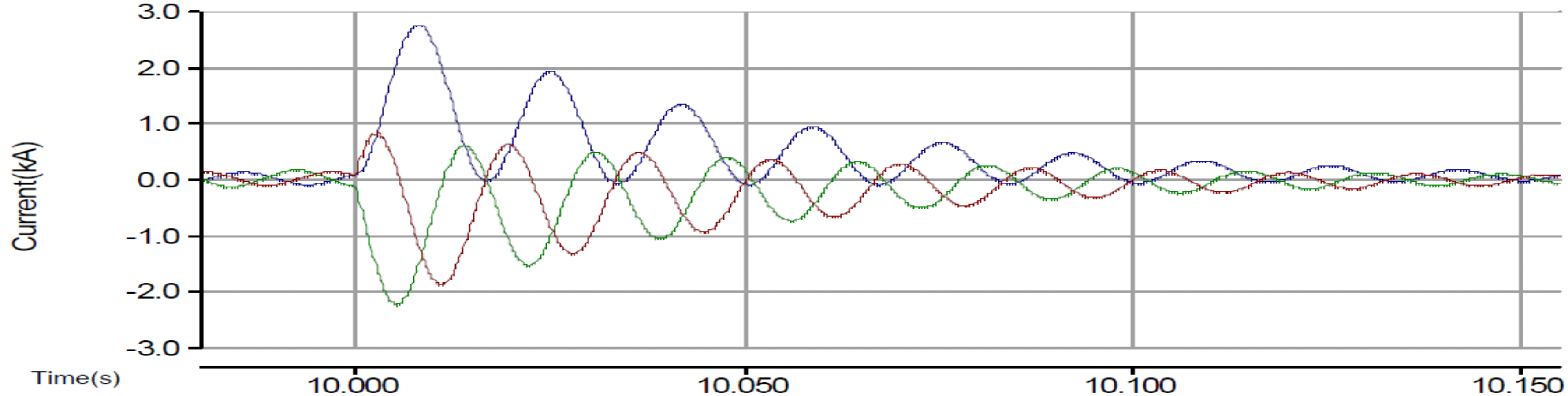




Comparison of synchronous (a) and induction (b) generators Short-circuit currents



(a)



(b)

DFIG Short-circuit at the Terminal

The stator voltage equation of the induction machine is determined as follows:

$$\underline{u}_s = R_s \underline{i}_s + \frac{d\underline{\psi}_s}{dt} + j\omega_s \underline{\psi}_s$$

When the voltage drops to zero (in case of a fault at the generator terminals), the stator flux space vector stops rotating (dc component). This produces big current oscillations in rotor windings and, consistently, high voltage in supplying converter scheme.

Remedium is adequate *protection*.

Grid Code requirements

The latest grid code requirements specify the behaviour of wind generators when dips occure:

- **under what type of dips the turbine must remain connected to the grid ;**
- **how much reactive power the wind generator must provide to the grid in order to contribute to the fault clearance.**

Grid Code: **a document establishing the rules governing the operation, maintenance and development of the power system and sets out the procedures for governing the actions of all power system users.**

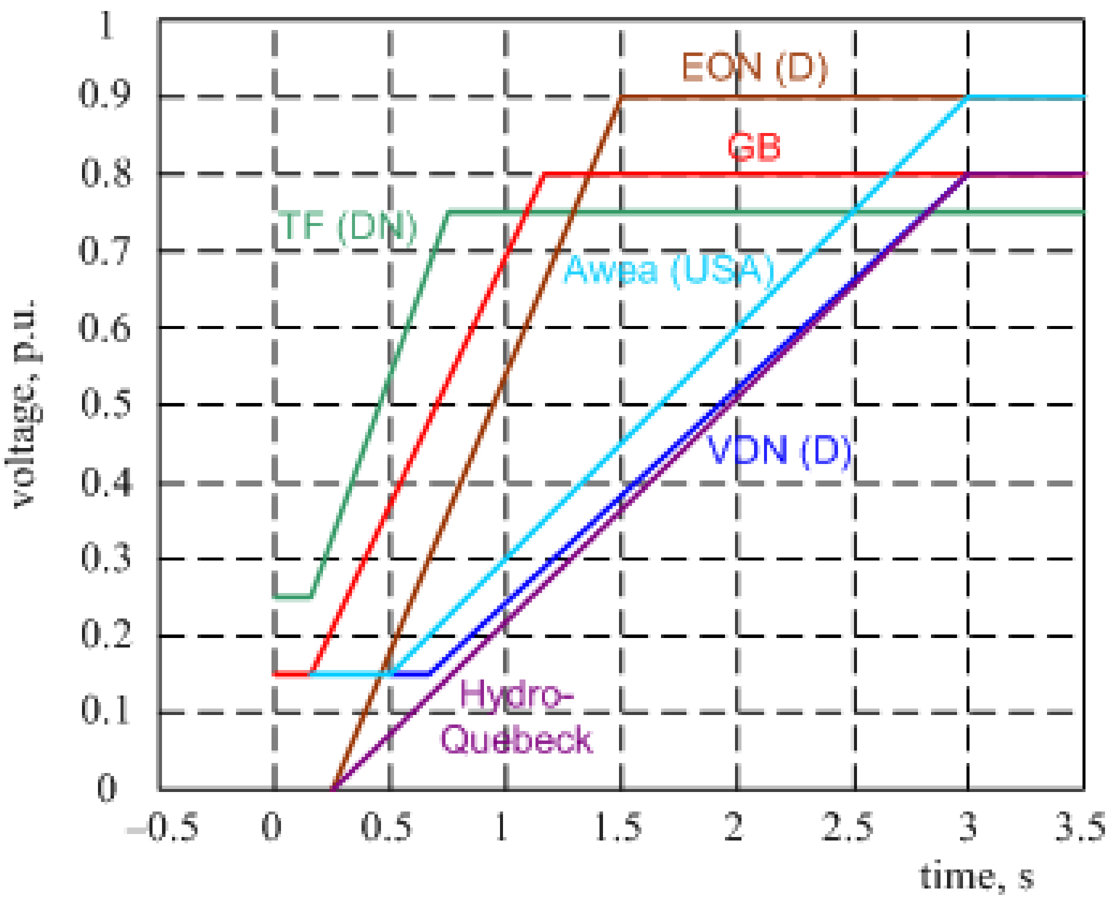
Low Voltage Ride-through (LVRT)

The LVRT requirements specify the above conditions (the wind generators connection to grid and demands of reactive power).

The main requirement is the ability of wind generator to remain connected to the grid during and after faults. This is known as low voltage ride through ability.

Different countries define their own Grid Code requirements.

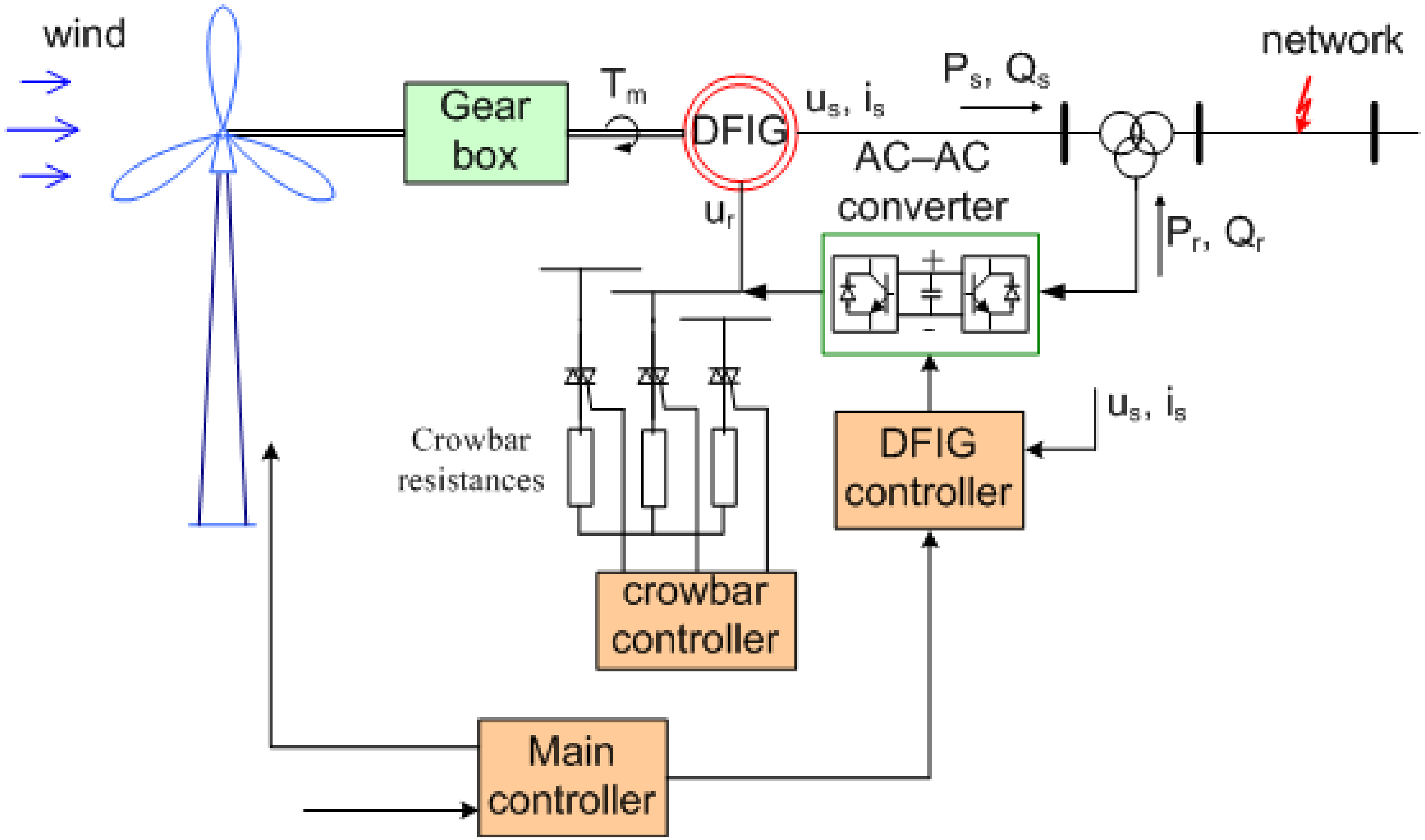
Low Voltage Ride-through requirements for different grid codes



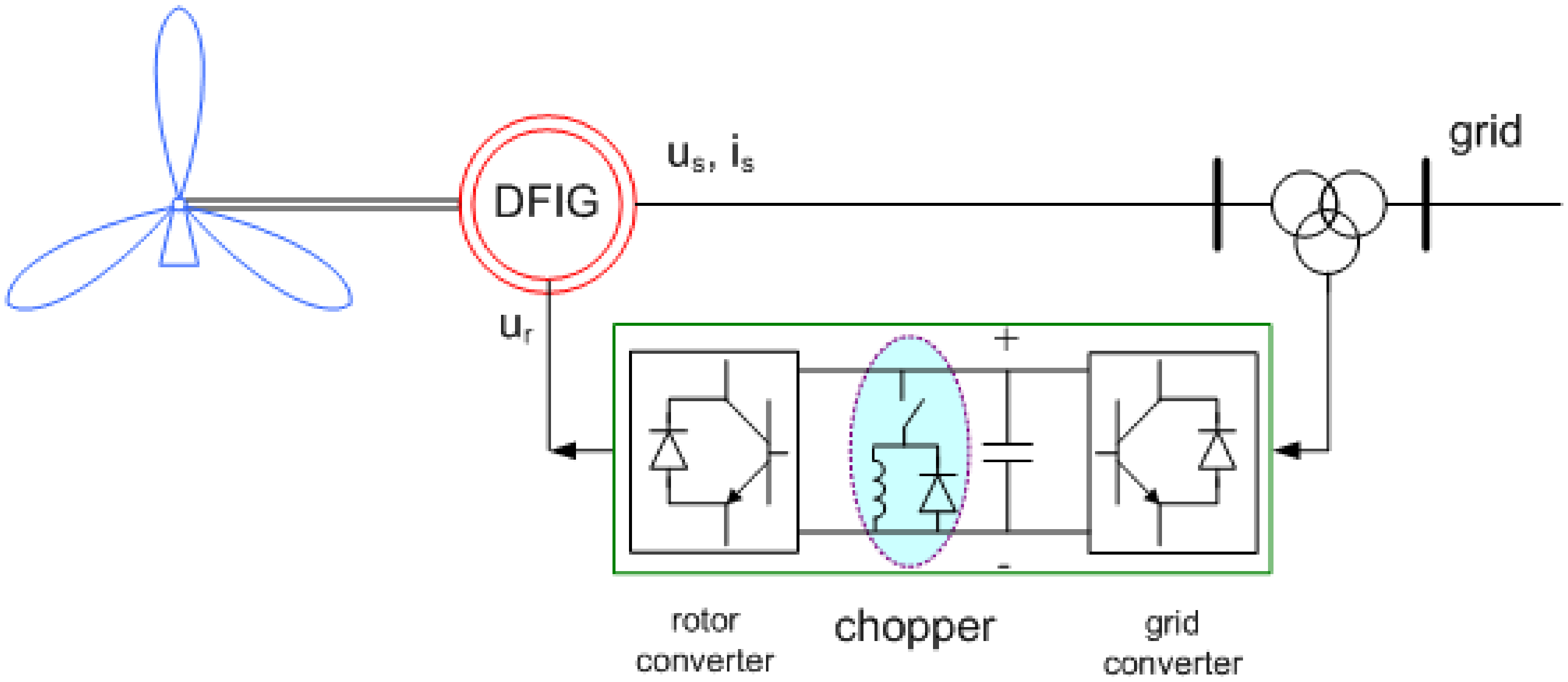
DFIG protection methods

1. **Software protection: adequate control of electronic converters in case of:**
   - **unbalance condition (unbalance load or unbalance voltage);**
   - **small voltage dip.**
2. **Hardware protection:**
   - **crowbar activation;**
   - **braking chopper;**
   - **replacement loads;**
   - **series resistors.**

Crowbar application

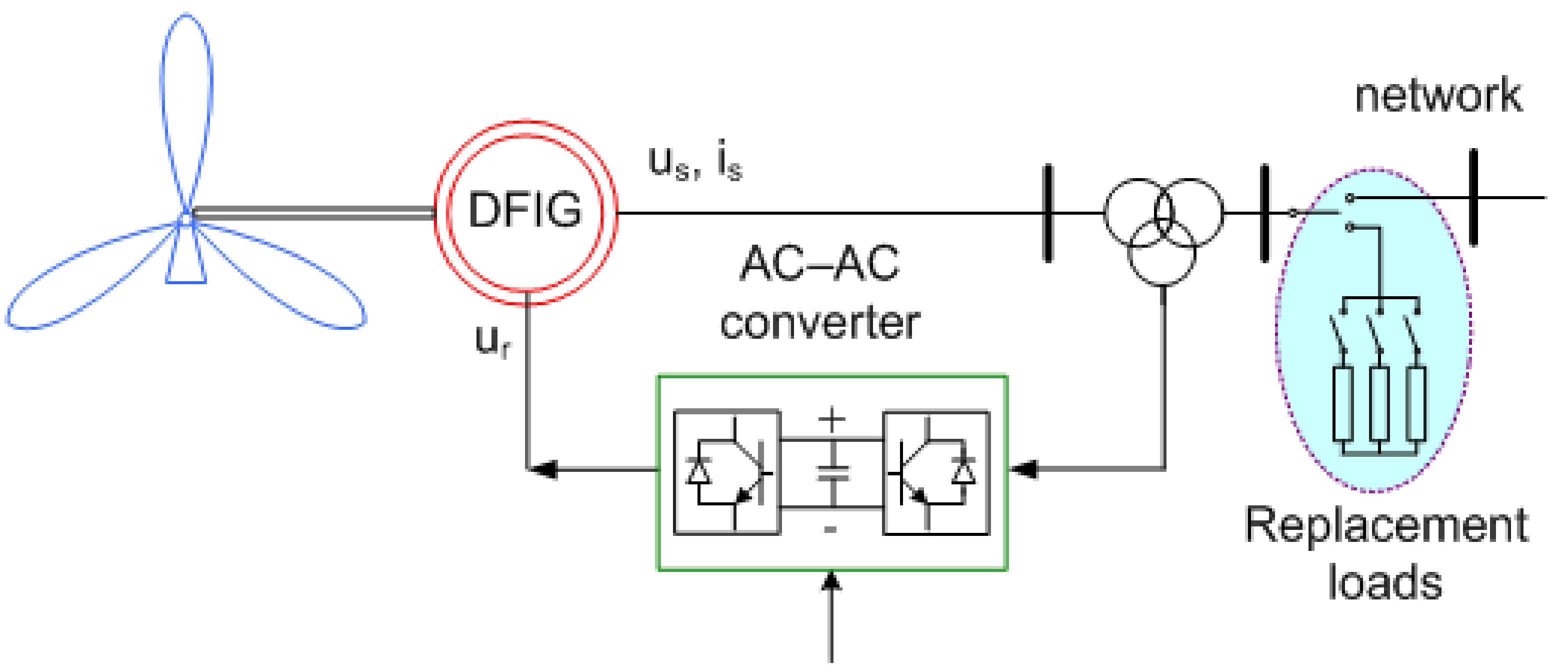


Breaking chopper application



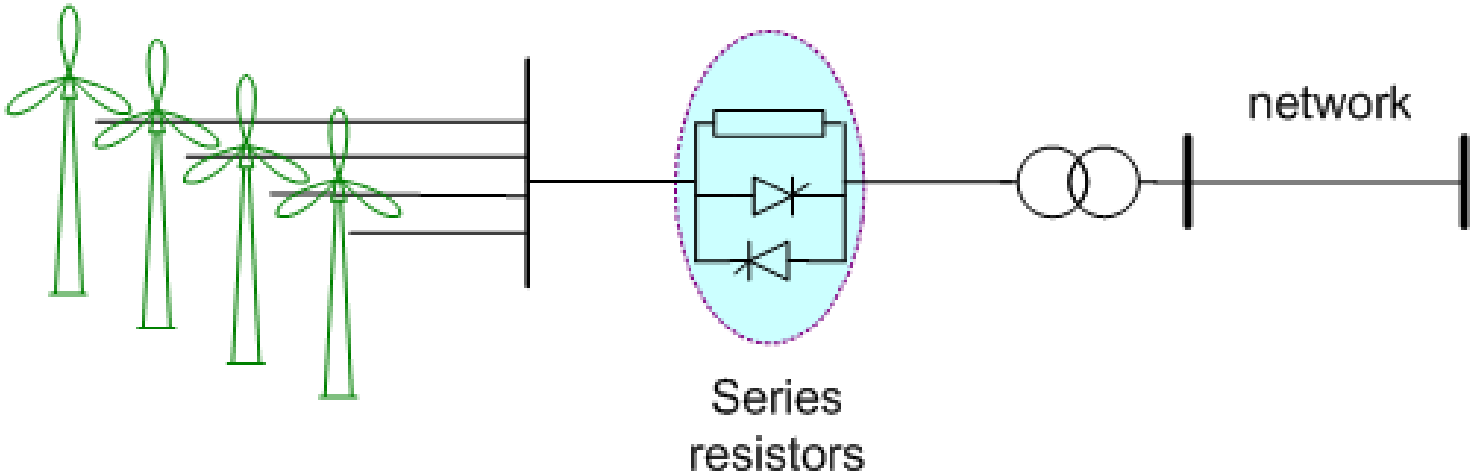
Usually applied with a crowbar

Replacement loads application



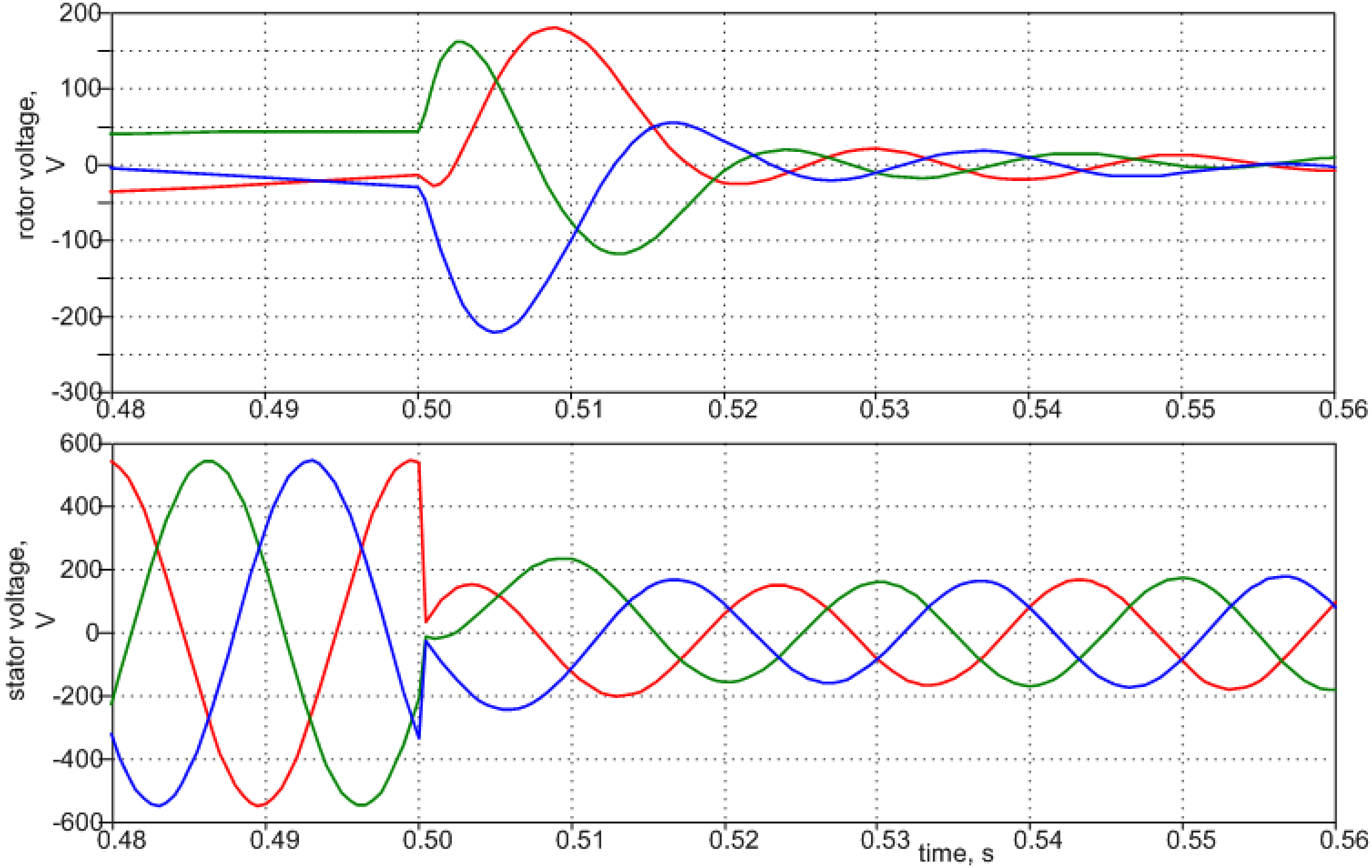
Usually applied with a crowbar

Series resistors application

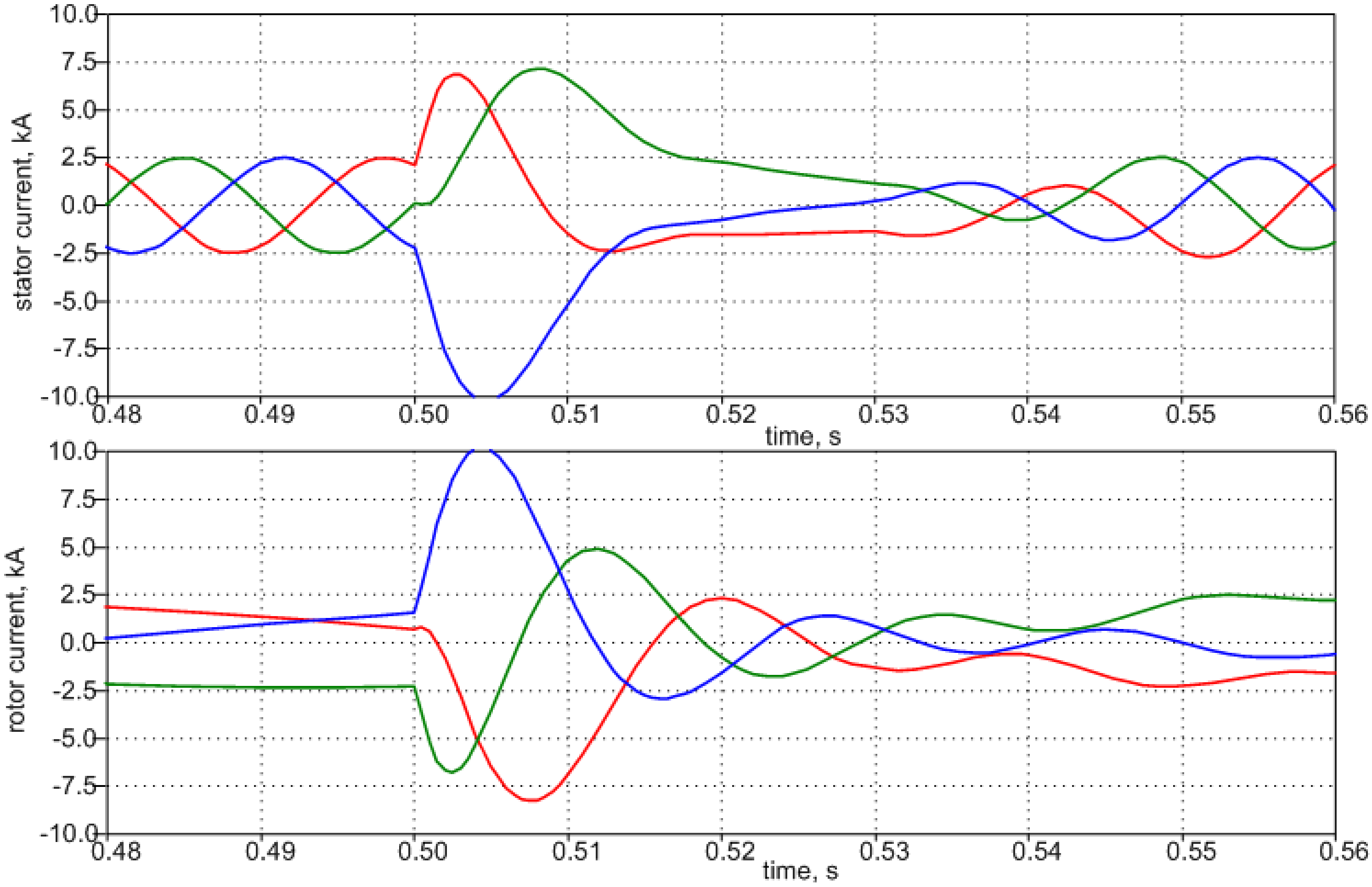


Usually installed in a wind farm

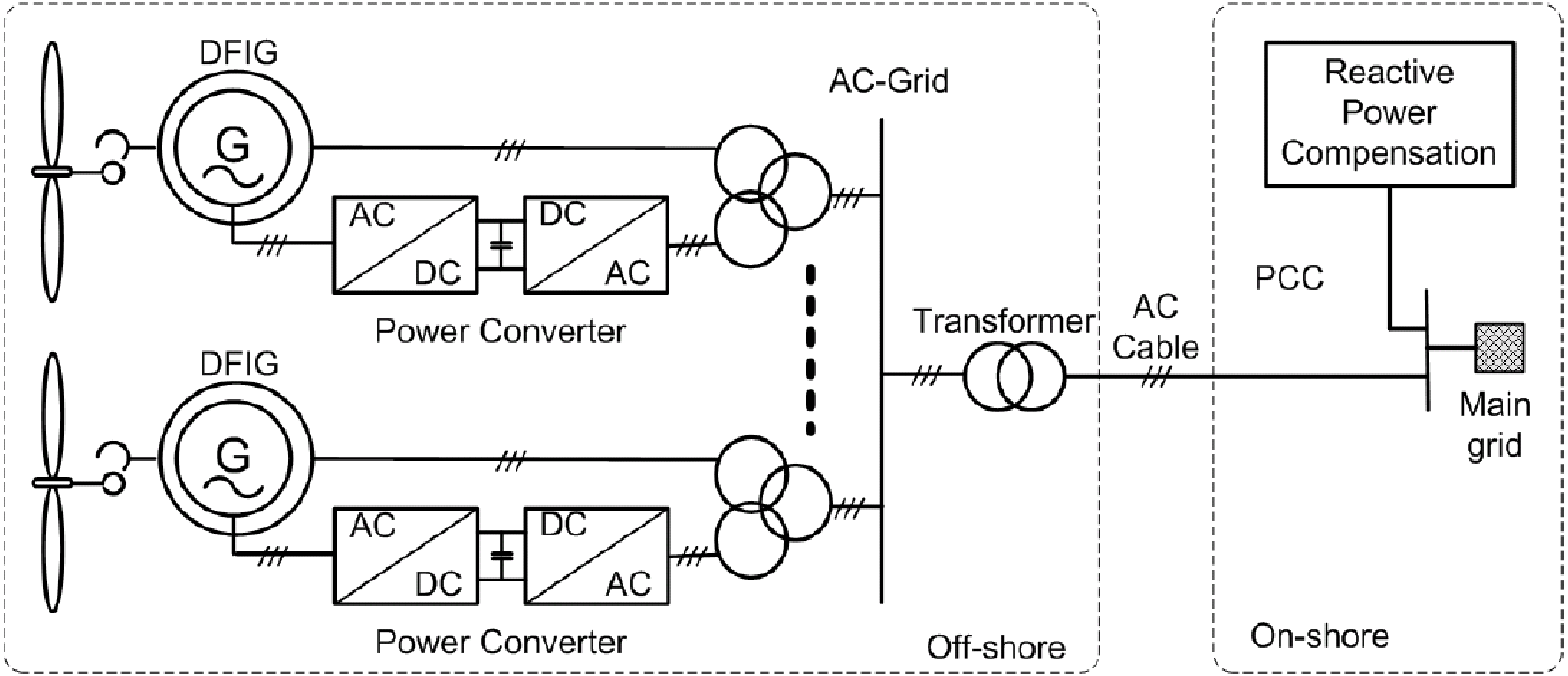
DFIG Short-circuit Voltages



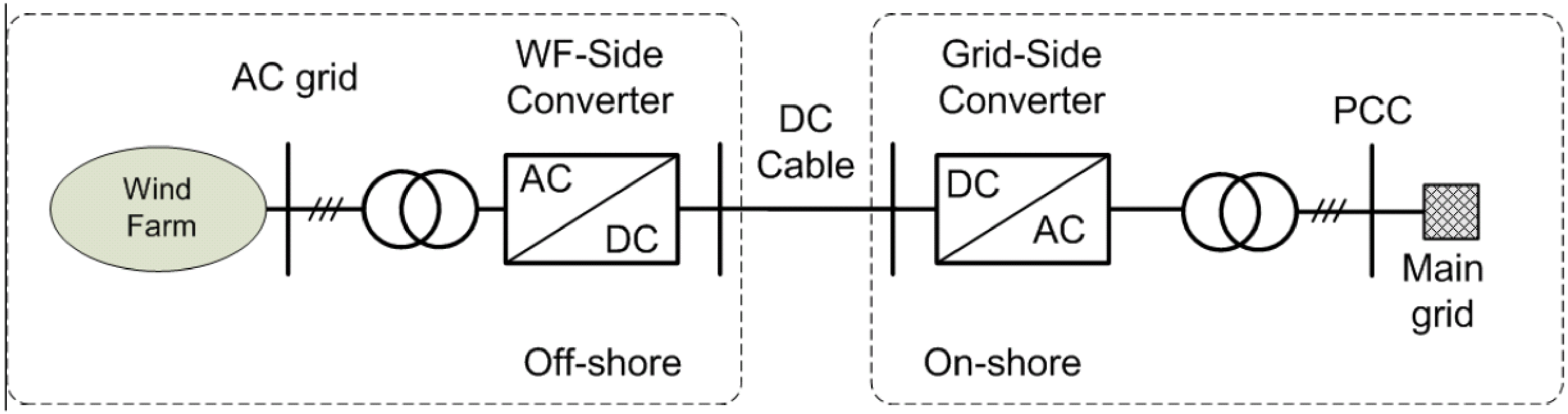
DFIG Short-circuit Currents



Wind Farm Interconnection



Wind Farm Interconnection



HVDC Connection of the Off-shore Farm