Utility Integration of Wind Energy Systems

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Contents

Chapter 1
Wind Energy Systems Overview

1.1 Historical Development

- Wind power in sailboats was used several thousand years ago
- The Babylonian emperor Hammurabi planned to use wind power for his ambitious irrigation project during seventeenth century B.C.
- The wind wheel of the Greek engineer Heron of Alexandria in the 1st century AD is the earliest known instance of using a wind-driven wheel to power a machine
- wind-driven wheel was the prayer wheel, which was used in ancient Tibet and China since the 4th century

By the 13th century, grain grinding mills were popular in most of Europe

French adopted this technology by 1105 A.D. and the English by 1191 A.D

Fig.1.1 Old windmill.

The era of wind electric generators began close to 1900’s.

The first modern wind turbine, specifically designed for electricity generation, was constructed in Denmark in 1890.

The first utility-scale system was installed in Russia in 1931.

A significant development in large-scale systems was the 1250 kW turbine fabricated by Palmer C. Putman.

Fig.1.2 Mod-5B Horizontal axis wind turbine.

Fig.1.3 Darrieus wind turbine is vertical axis wind turbine.

Current status and future prospects

Wind is the world’s fastest growing energy source today

The global wind power capacity increases at least 40% every year.

For example, the European Union targets to meet 25 per cent of their demand from renewable by 2012.

Spain also celebrates in Nov. 10, 2010 when the wind energy resources contribute 53% of the total generation of the electricity.

Over 80 percent of the global installations are in Europe.

Installed capacity may reach a level of 1.2 million MW by 2020

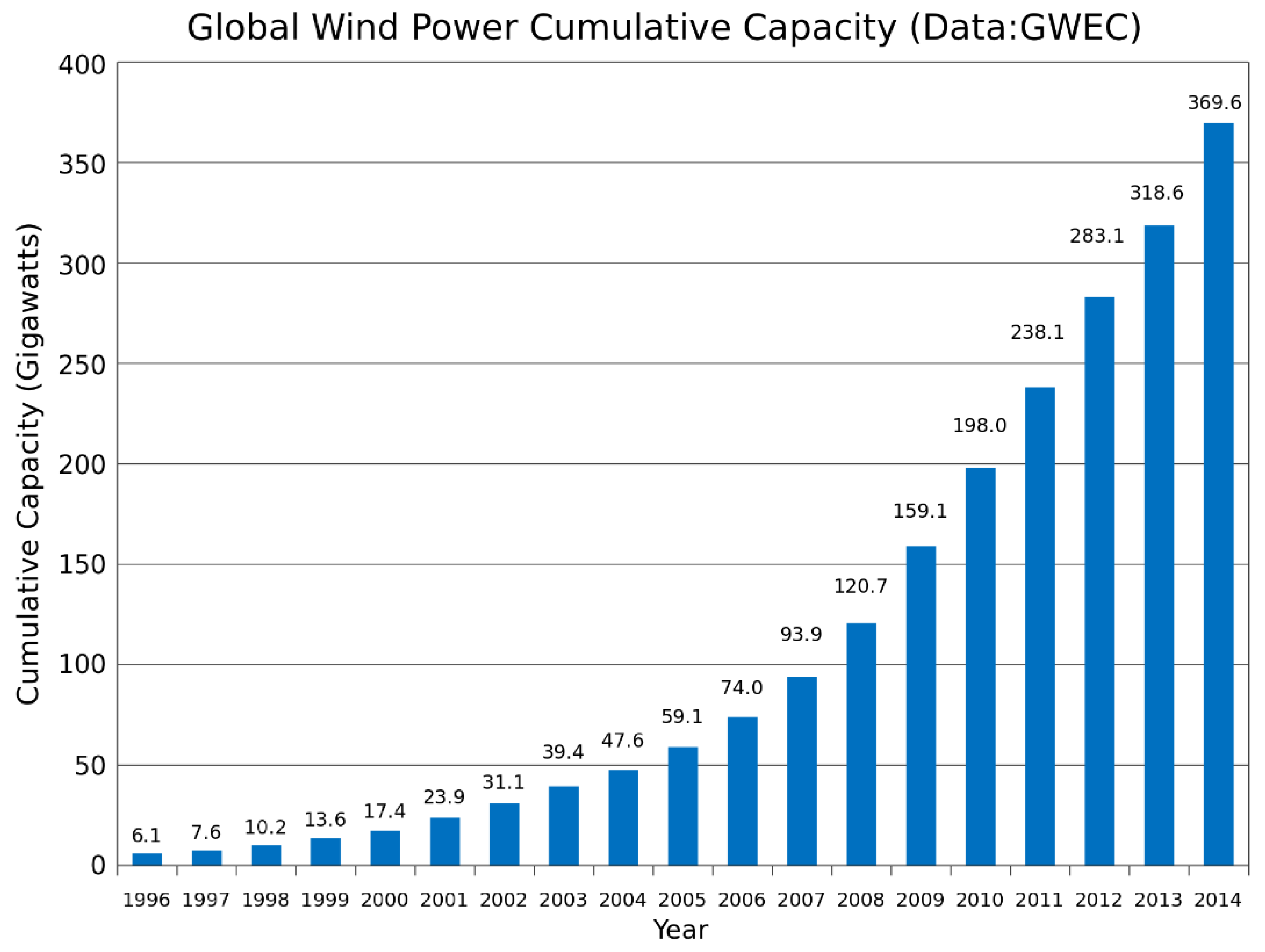
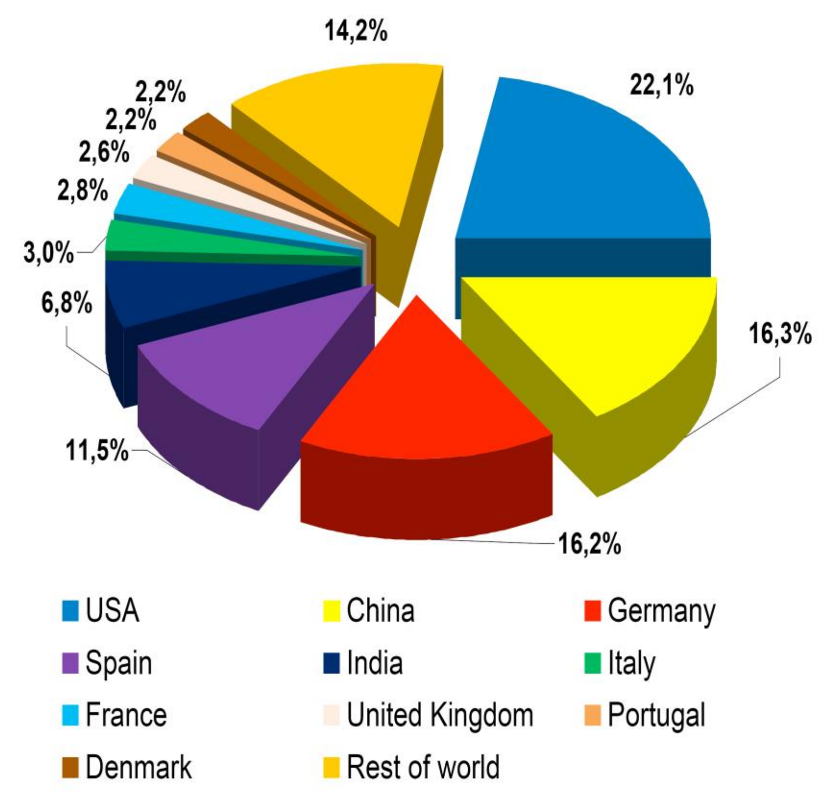


Fig.1.4 the installed capacity from the wind worldwide.



Wind Power Worldwide June 2010

Position	Country	Total capacity June 2010 [MW]	Added capacity June 2010 [MW]	Total capacity end 2009 [MW]
1	USA	**36.300**	1.200	35.159
2	China	**33.800**	7.800	26.010
3	Germany	**26.400**	660	25.777
4	Spain	**19.500**	400	19.149
5	India	**12.100**	1.200	10.925
6	Italy	**5.300**	450	4.850
7	France	**5.000**	500	4.521
8	United Kingdom	**4.600**	500	4.092
9	Portugal	**3.800**	230	3.535
10	Denmark	**3.700**	190	3.497
	Rest of the World	**24.500**	2.870	21.698
Total		**175.000**	**16.000**	**159.213**

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Fig. 1.5 Installed capacity in different regions in the world, 2010.

(a) SWAY 10MW.

Enercon E126, 7.5MW, 126 diameter•

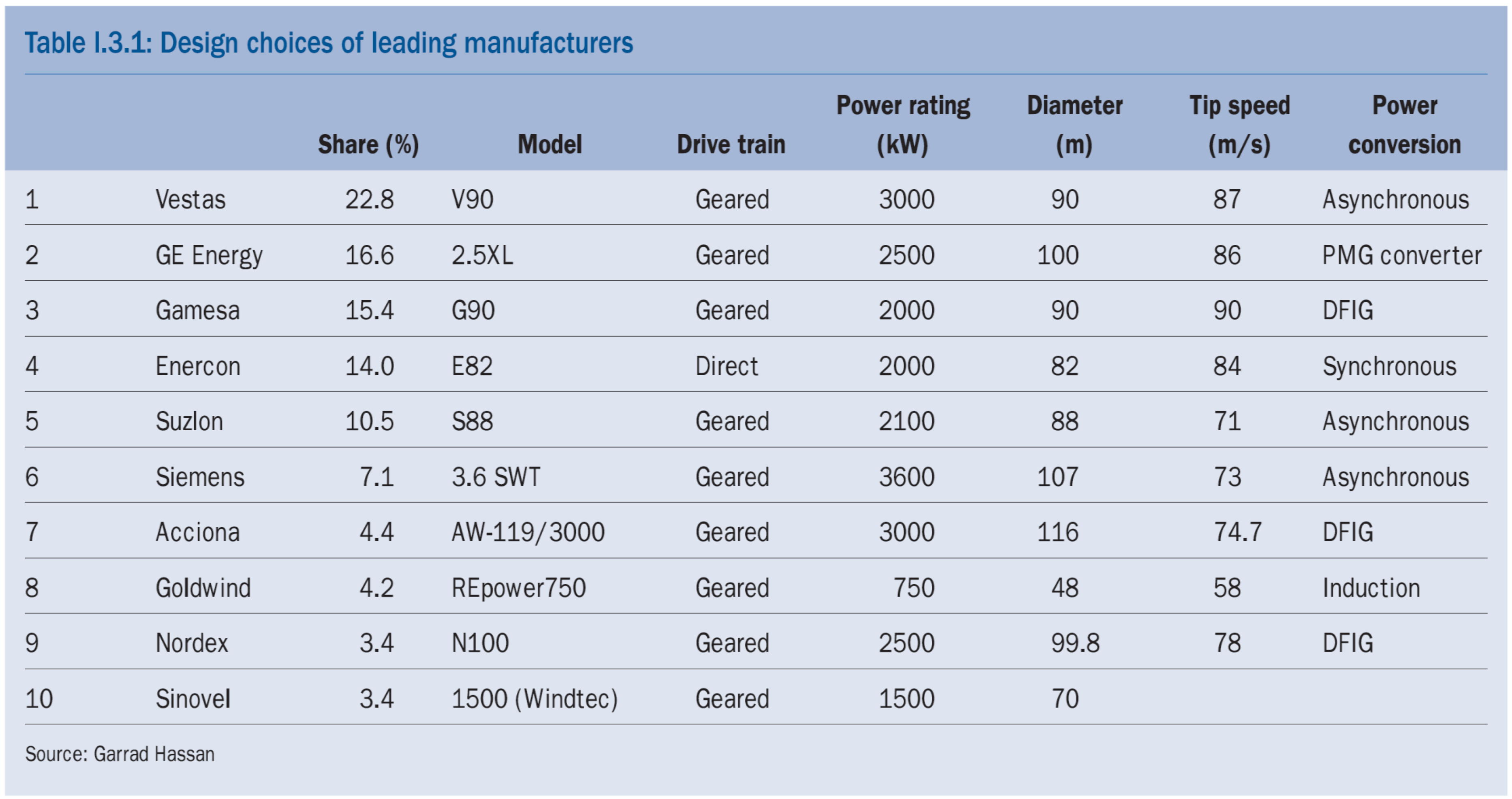


Table I.3.1: Design choices of leading manufacturers

		Share (%)	Model	Drive train	Power rating (kW)	Diameter (m)	Tip speed (m/s)	Power conversion
1	Vestas	22.8	V90	Geared	3000	90	87	Asynchronous
2	GE Energy	16.6	2.5XL	Geared	2500	100	86	PMG converter
3	Gamesa	15.4	G90	Geared	2000	90	90	DFIG
4	Enercon	14.0	E82	Direct	2000	82	84	Synchronous
5	Suzlon	10.5	S88	Geared	2100	88	71	Asynchronous
6	Siemens	7.1	3.6 SWT	Geared	3600	107	73	Asynchronous
7	Acciona	4.4	AW-119/3000	Geared	3000	116	74.7	DFIG
8	Goldwind	4.2	REpower750	Geared	750	48	58	Induction
9	Nordex	3.4	N100	Geared	2500	99.8	78	DFIG
10	Sinovel	3.4	1500 (Windtec)	Geared	1500	70		

Source: Garrad Hassan

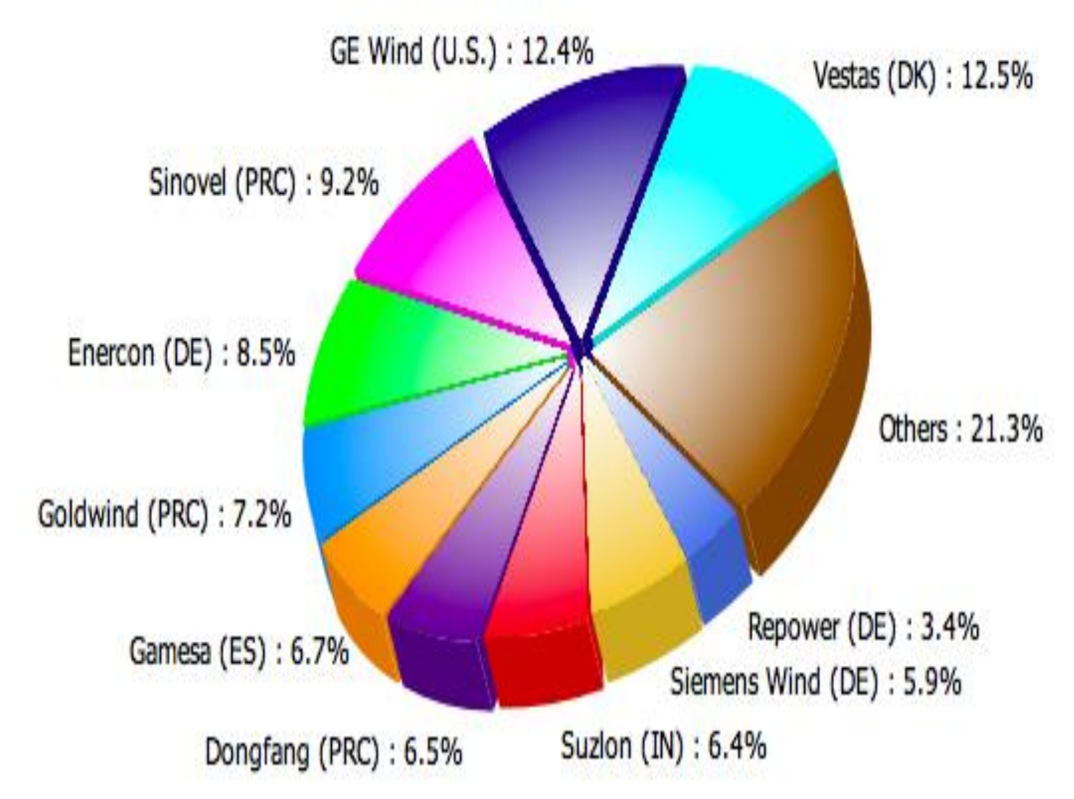


Fig.1.7 Top ten manufacturers of WTs, 2009.

1.3.1 Large Diameter

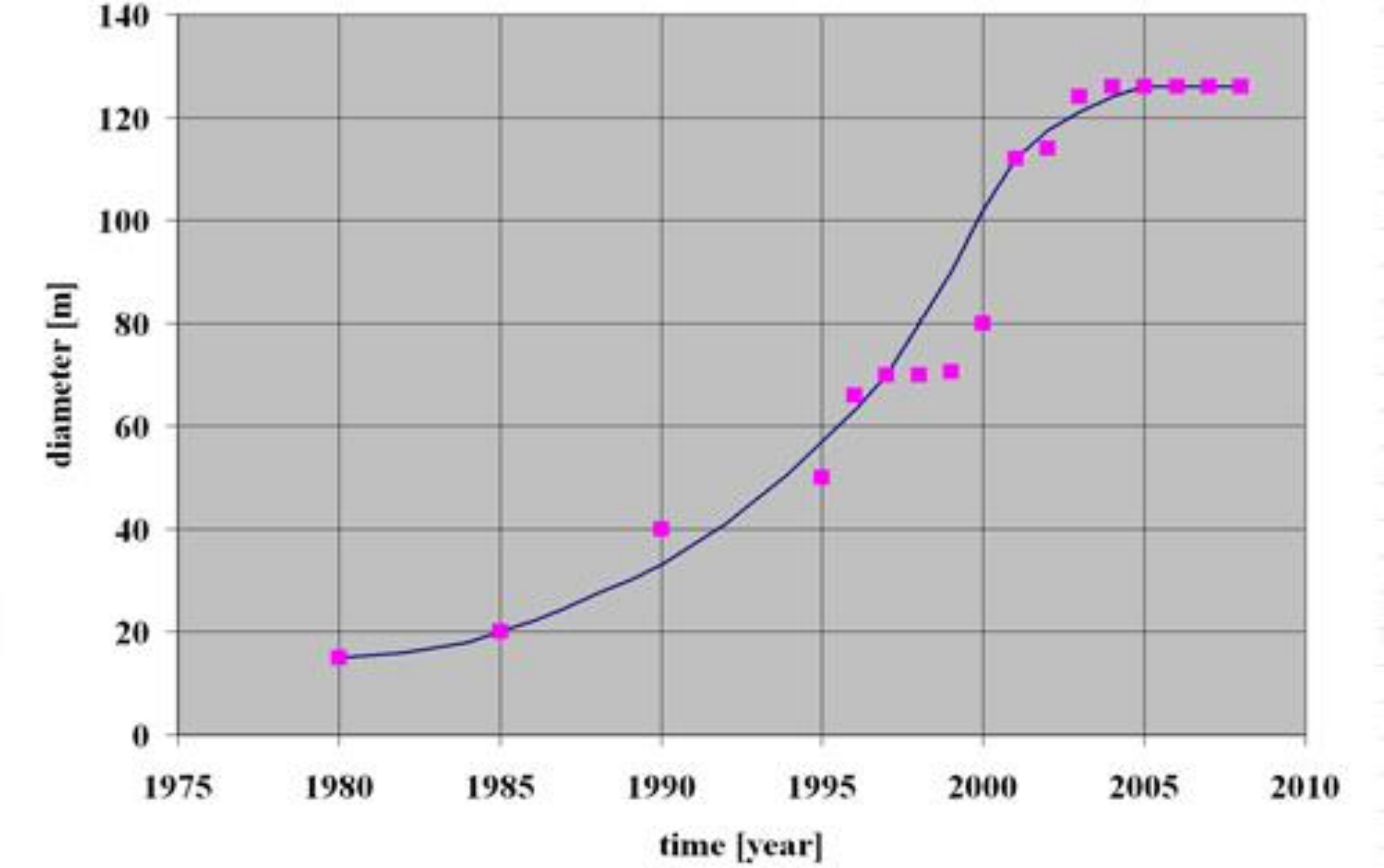
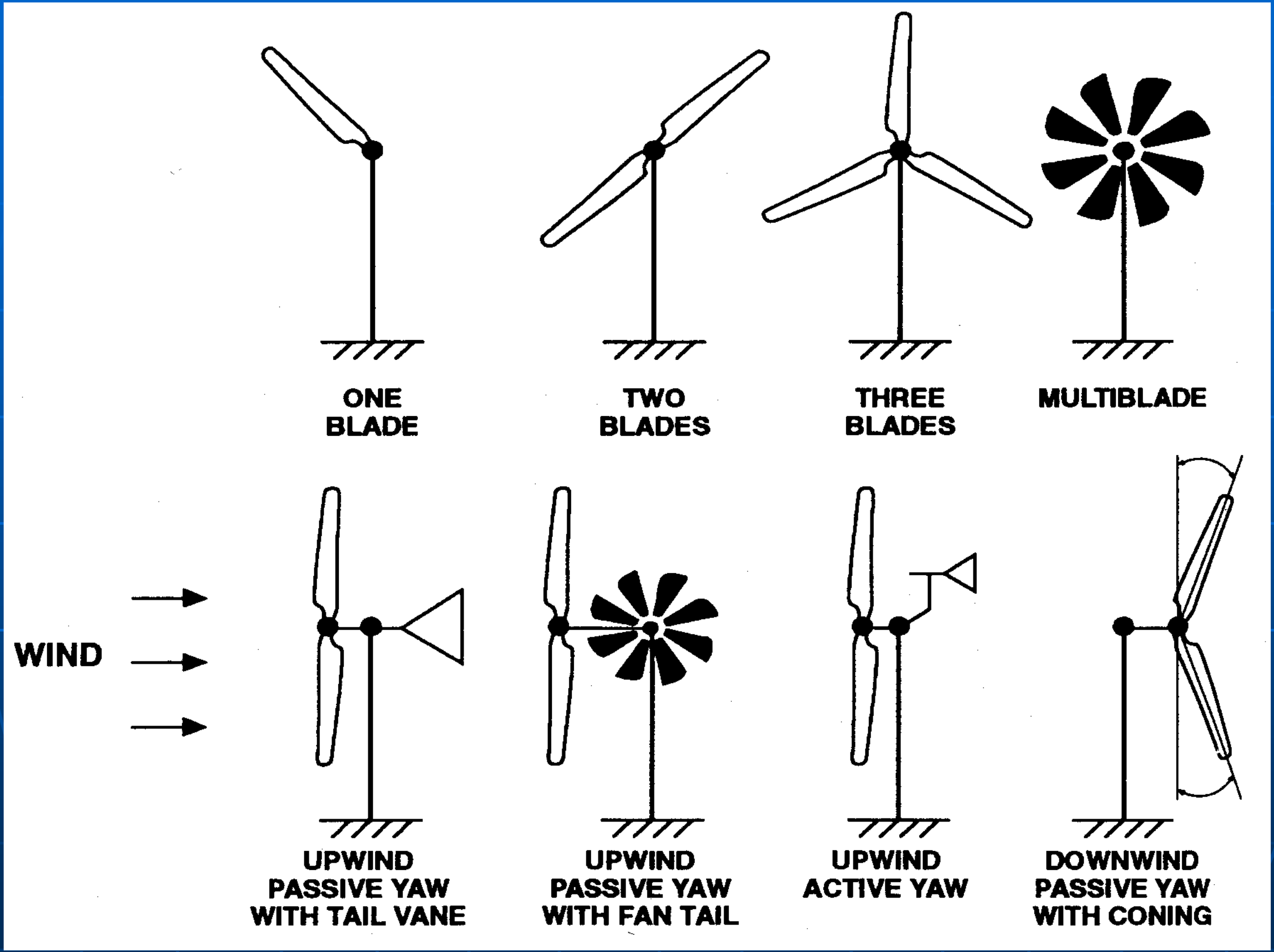


Fig.1.8 Turbine diameter growth with time.

1.3.2 Types of Wind Turbine Generators (WT)



The HAWT configurations

Vertical Axis WTs (VAWTs)

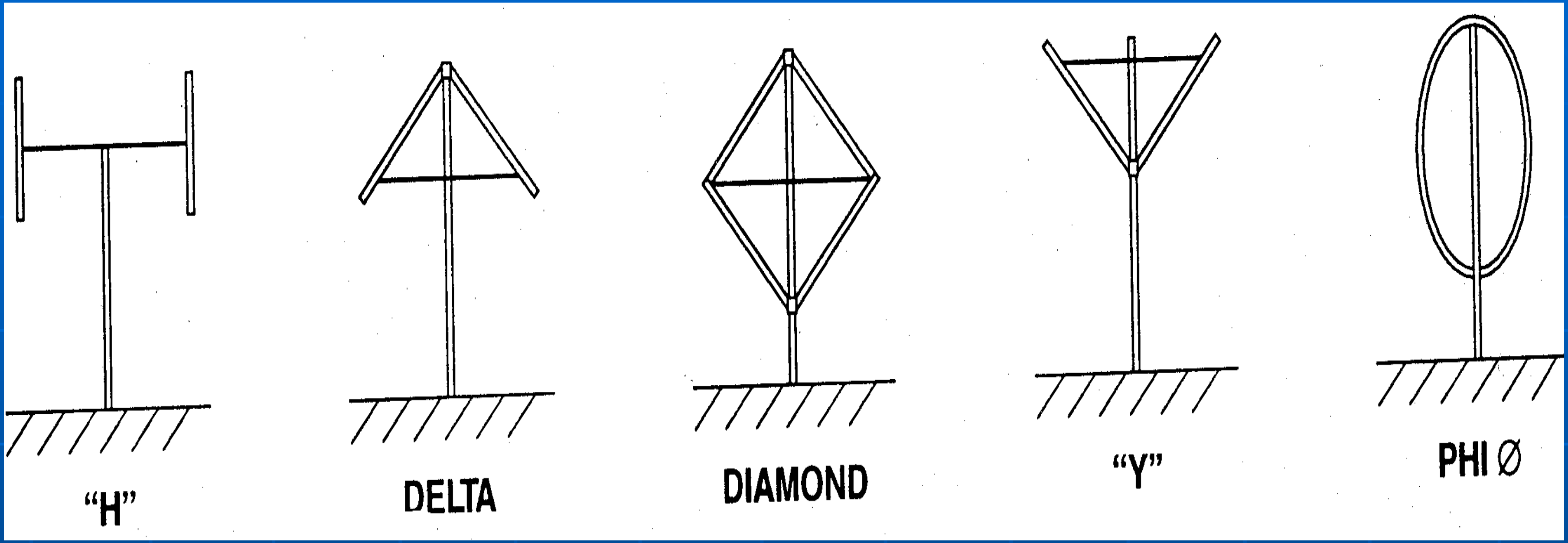
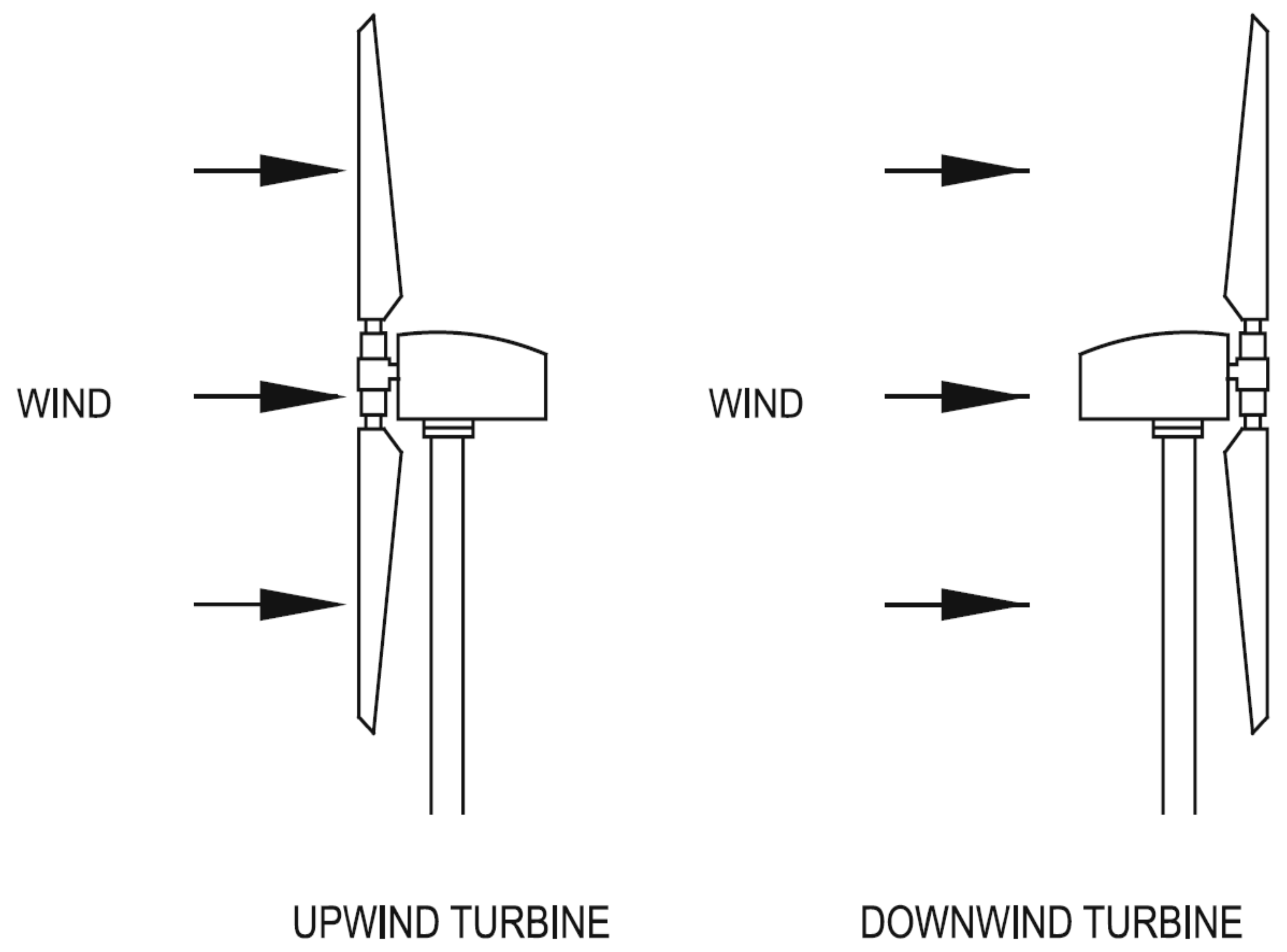


Fig. 1.10 The VA-WTs Configurations

Table (1.2) Comparison between HA-WTs and VA-WTs.

Items	**HA-WTs**	**VA-WTs**
Output power	Wide range	Narrow range
Starting	Self starting	Need starting means
Efficiency	Higher	Lower
Cost	Lower	Higher
Wind direction	Need redirected when the Wind change its direction	Does not needs redirected into the wind direction
Generator and gear box	At the top of the tower	At the ground level
Maintenance	Difficult	Easy

1.3.3 Upwind and Dawnwind WT



Upwind turbines have the rotor facing the wind as shown in Fig.1.11 (a). This technique has the following features:

- Avoids the wind shade that the tower causes which improve the power quality of the generated voltage and reduces the spicks in power when the blades move in front of the tower specially in constant speed systems.
- Fewer fluctuations in the power output.
- Requires a rigid hub, which has to be away from the tower. Otherwise, if the blades are bending too far, they will hit the tower.
- This is the dominant design for most wind turbines in the MW- range

Downwind WT have the rotor on the flow-side as shown in Fig.1.11 (b). It may be built without a yaw mechanism if the nacelle has a streamlined body that will make it follow the wind.

- Rotor can be more flexible: Blades can bend at high speeds, taking load off the tower. Allow for lighter build.
- Increased fluctuations in wind power, as blades are affected by the tower shade.
- Only small wind turbines.

1.3.4Number of Rotor Blades

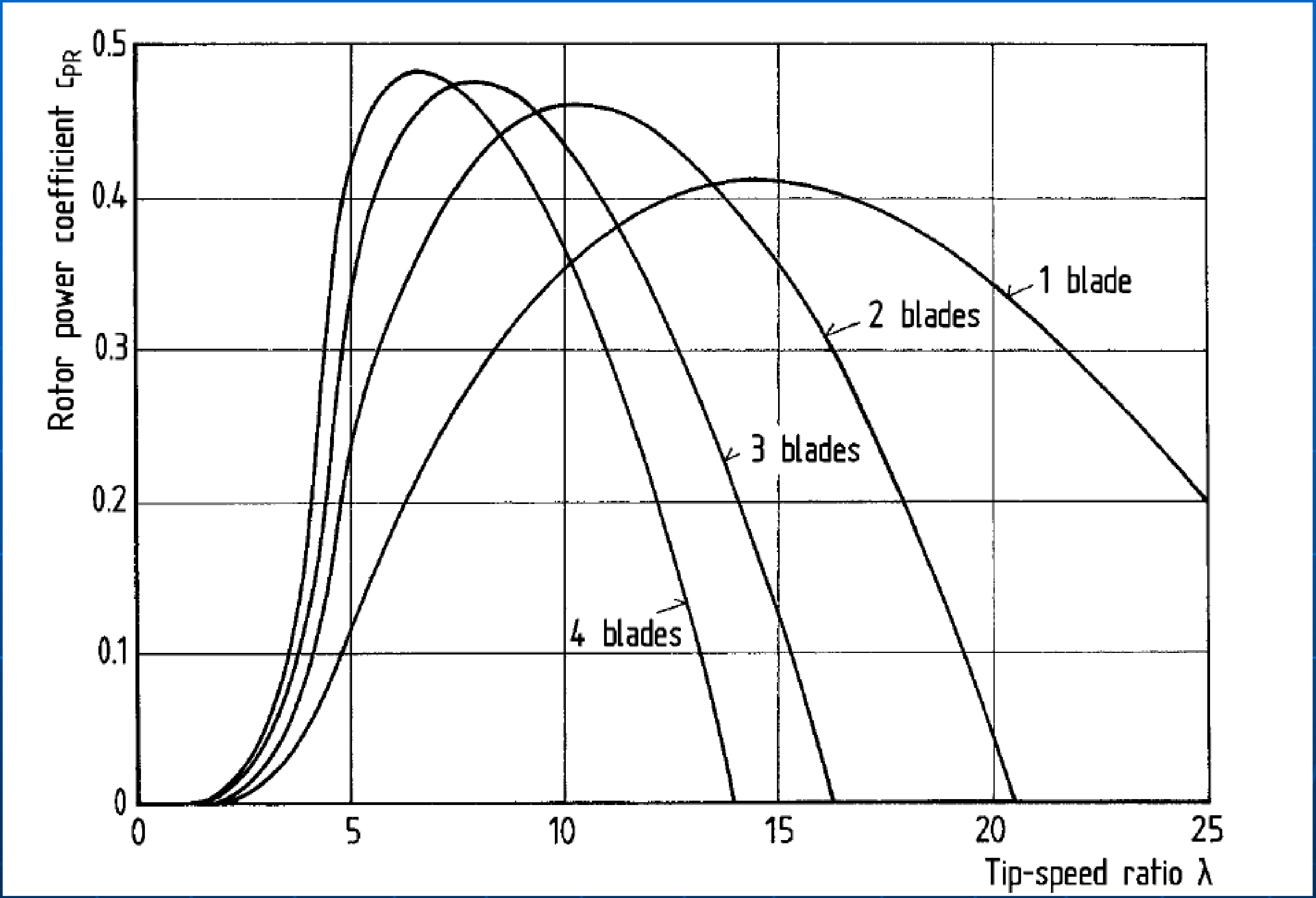


Fig.1.12. Influence of the number of blades on the rotor power coefficient (envelope) and the optimum tip-speed ratio.

Tip Speed Ratio

$$\text{Tip speed ratio } \lambda = \frac{u}{v_\omega} = \frac{\text{tangential velocity of the rotor blade tip}}{\text{Speed of the wind}}$$

Fig..13 shows one blade WT.

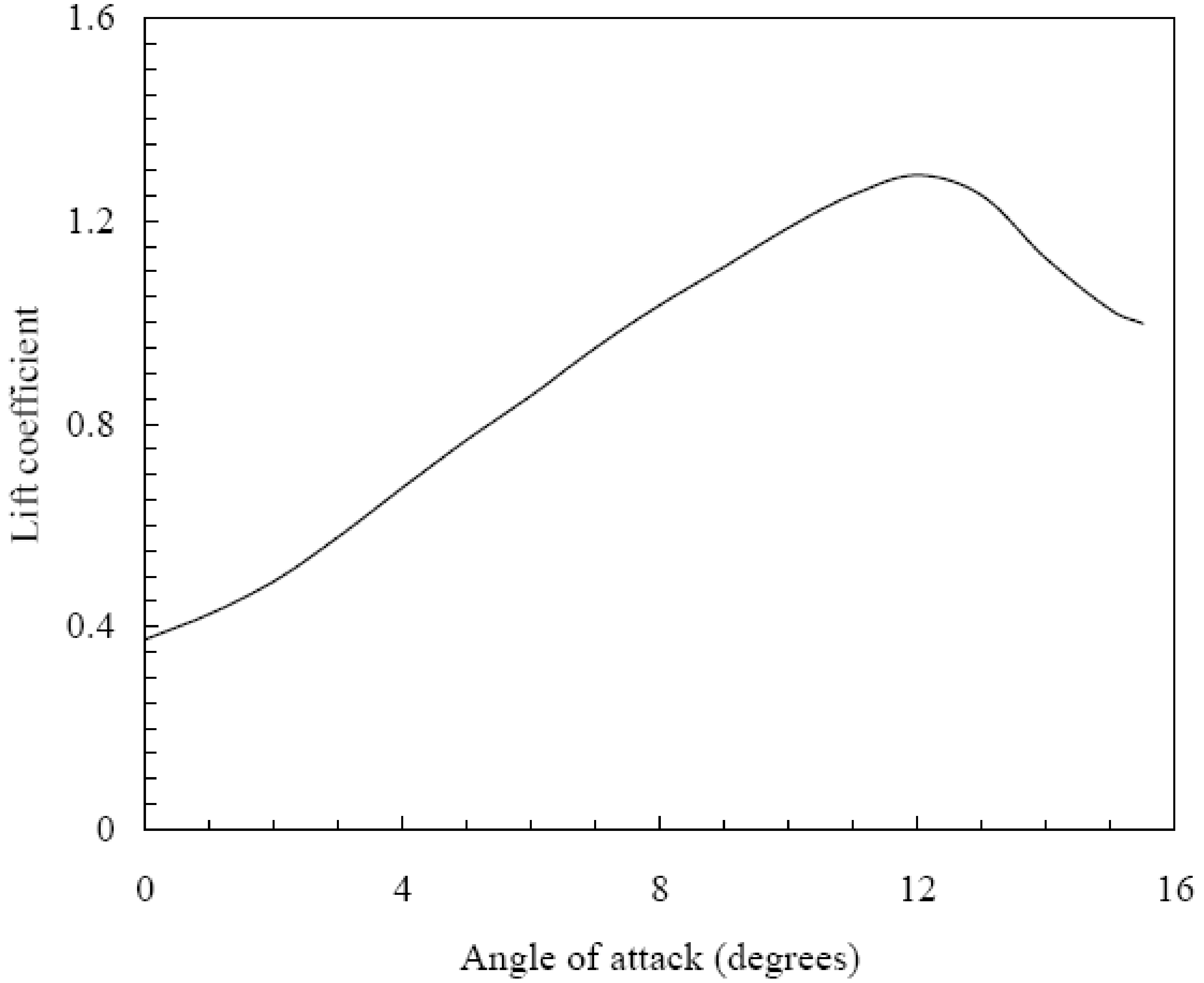


Fig.1.16. Effect of angle of attack on airfoil lift

1.Sitting of Wind Energy Plants

1.4.1 Wind Power

$$P_w = \frac{1}{2} \rho_a \; A \, V^3$$

where ρ_a : Air density, kg/m³.

A: Cross sectional area of wind parcel, m².

V: The wind speed, m/sec.

$$V(Z) = V(Zg)^* \left(\frac{Z}{Zg} \right)^{\alpha}$$

where Z : The height above the ground level, m.

Zg : The height of where the wind speed is measured, m.

α : The exponent, which depends on the roughness of the ground surface, its average value, is (1/7) [14].

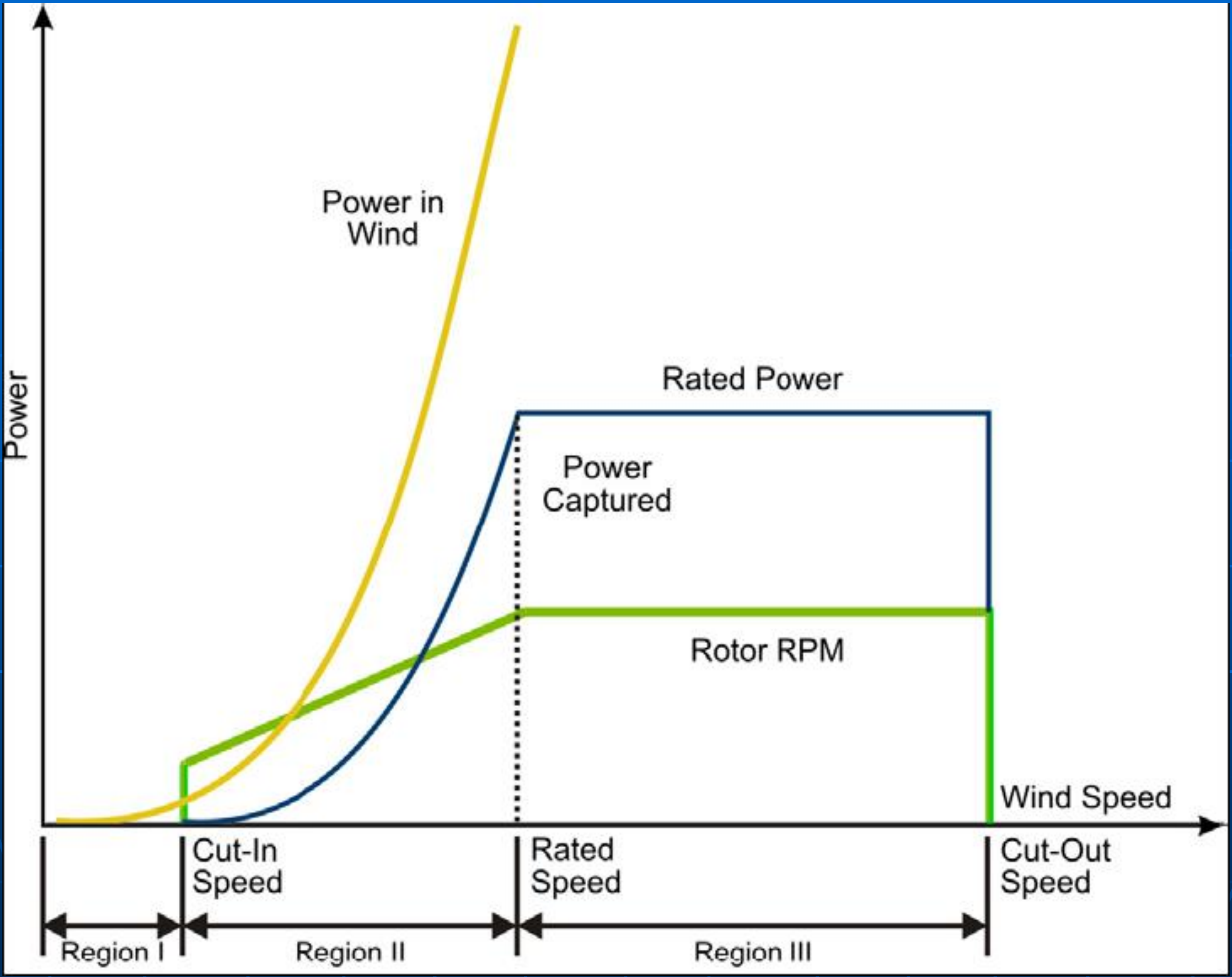


Fig. 1.22 Actual WT output power with the wind speed.

Design of Wind Energy System

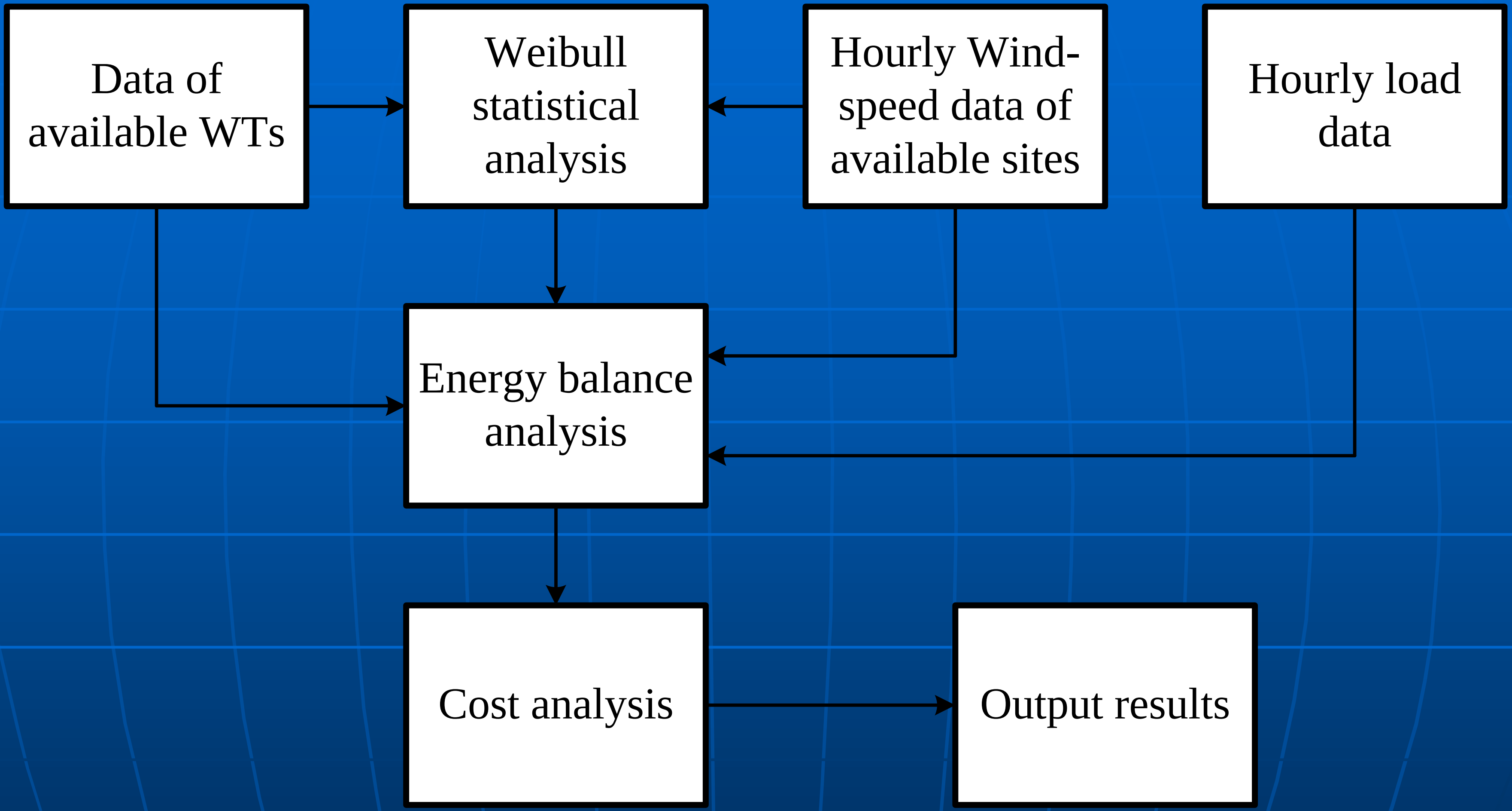
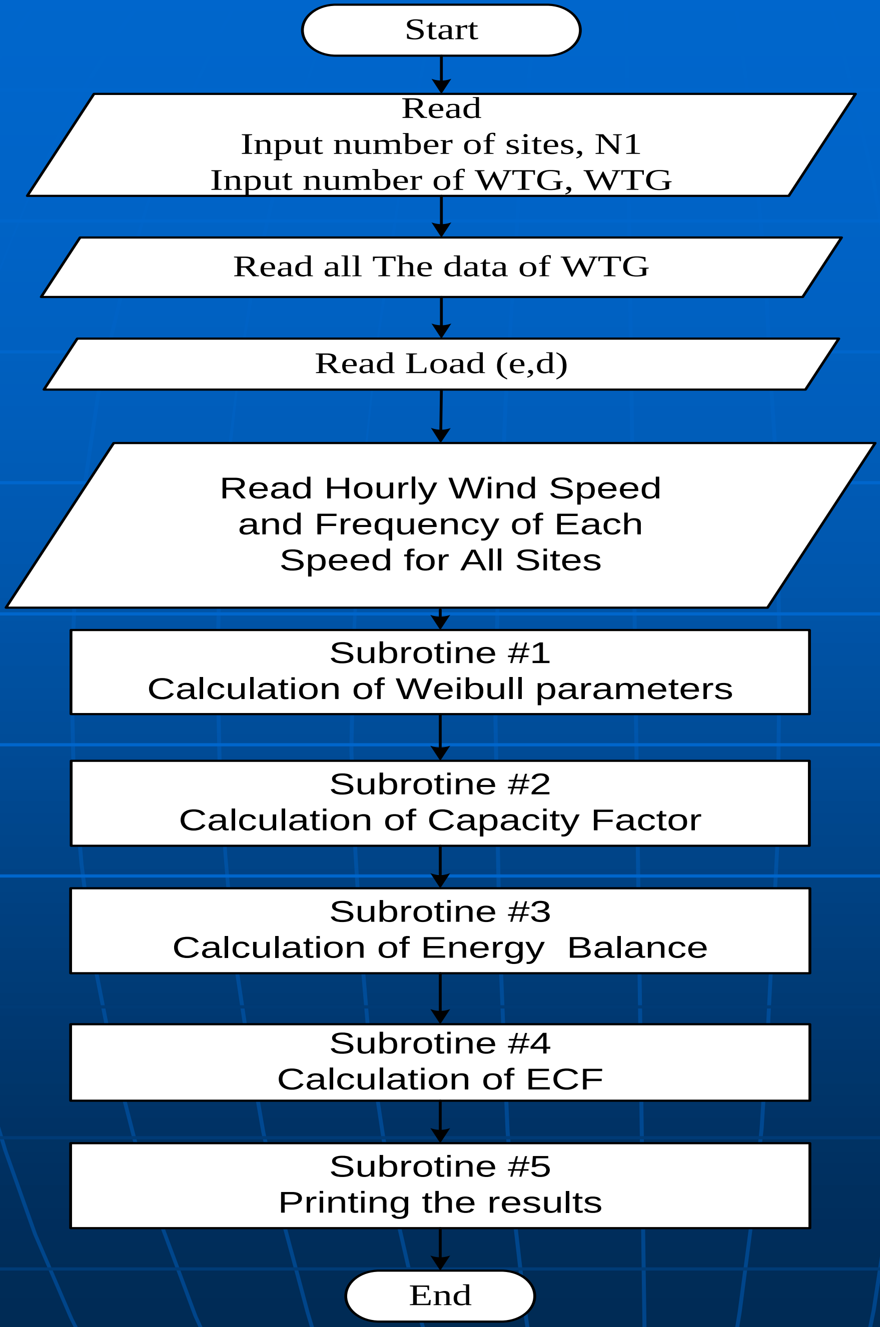


Fig.1.26 Summarized block diagram of the analysis



Start

Read
Input number of sites, N1
Input number of WTG, WTG

Read all The data of WTG

Read Load (e,d)

Read Hourly Wind Speed
and Frequency of Each
Speed for All Sites

Subrotine #1
Calculation of Weibull parameters

Subrotine #2
Calculation of Capacity Factor

Subrotine #3
Calculation of Energy Balance

Subrotine #4
Calculation of ECF

Subrotine #5
Printing the results

End

Fig.1.27 Flowchart of the main computer program.

Project Development

element of wind farm	% of total cost
Wind Turbines	65
Civil Works	13
Wind farm electrical infrastructure	8
Electrical network connection	6
Project development and management costs	8

Chapter 2
Wind Power in Power Systems

Current Status of Wind Power in Power Systems

In Germany, energy penetration of 35 %

Danish system operator, a penetration of 22 %

In Nov. 10, 2010, the contribution from wind in the total loads of Spain was 53%

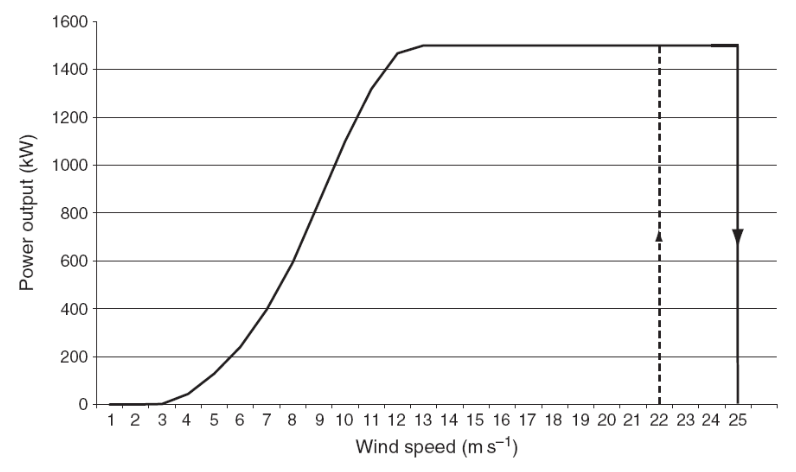
Network Integration Issues for Wind Power

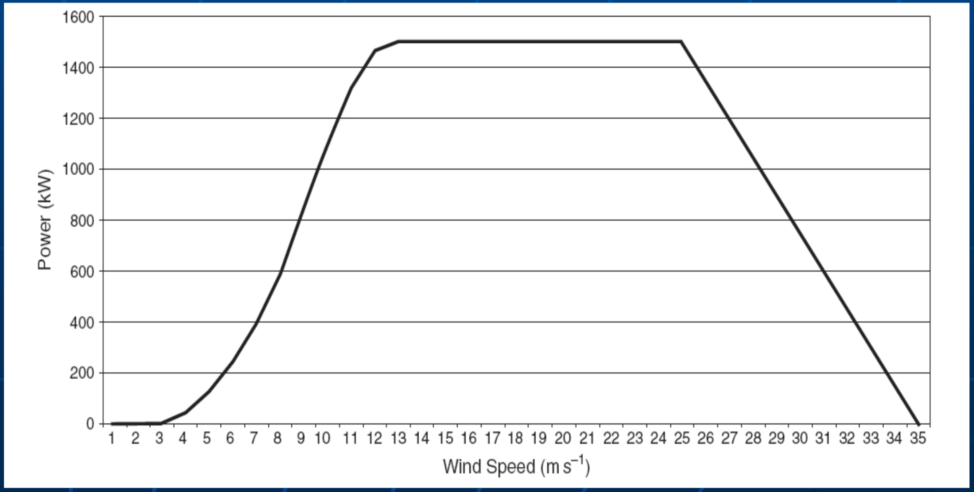
The basic challenge regarding the network integration of wind power consists therefore of the following two aspects:

•How to keep an acceptable voltage level for all consumers of the power system:

•customers should be able to continue to use the same type of appliances that they are used to.

Hysteresis and Cut-out Effect





Impact of Aggregation of Wind Power Production

The positive effect of wind power aggregation on power system operation has two aspects:

- an increased number of wind turbines within a wind farm;
- the distribution of wind farms over a wider geographical area.

Increased Number of Wind Turbines within a Wind Farm

An increased number of wind turbines reduces the impact of the turbulent peak, as gusts do not hit all the wind turbines at the same time.

Under ideal conditions, the percentage variation of power output will drop as $n^{-1/2}$, where n is the number of wind generators.

Distribution of Wind Farms over a Wider Geographical Area

A wider geographical distribution reduces the impact of the diurnal and synoptic peak significantly as changing weather patterns do not affect all wind turbines at the same time.

Basic Integration Issues Related to Wind Power

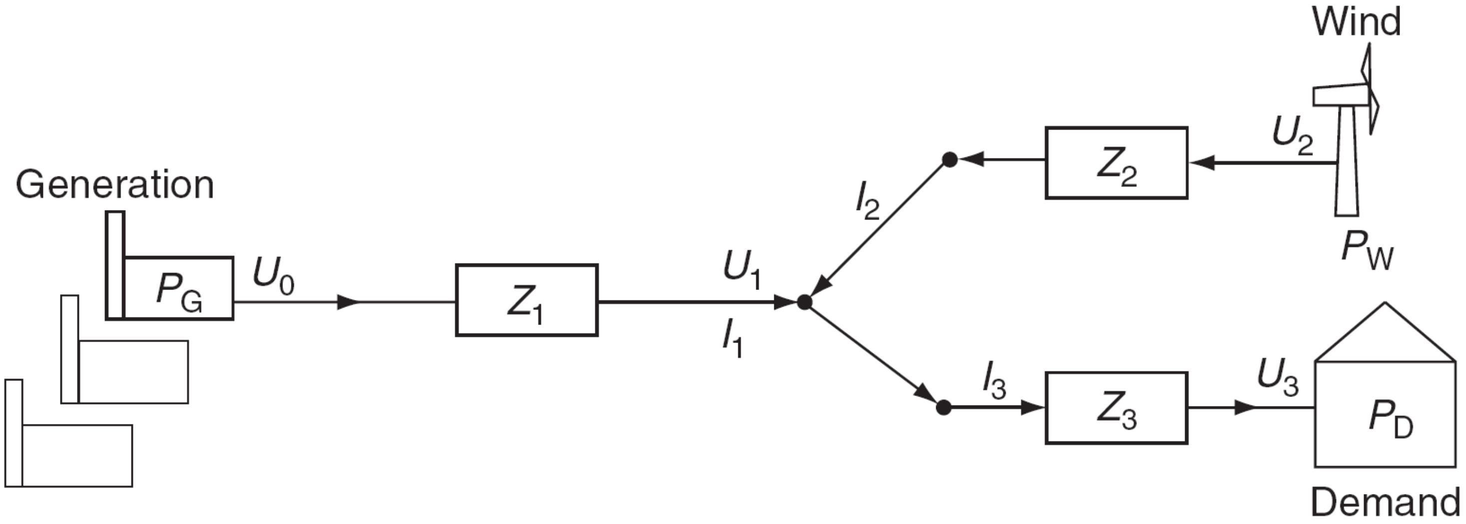


Fig.2.3 Illustrative power system.

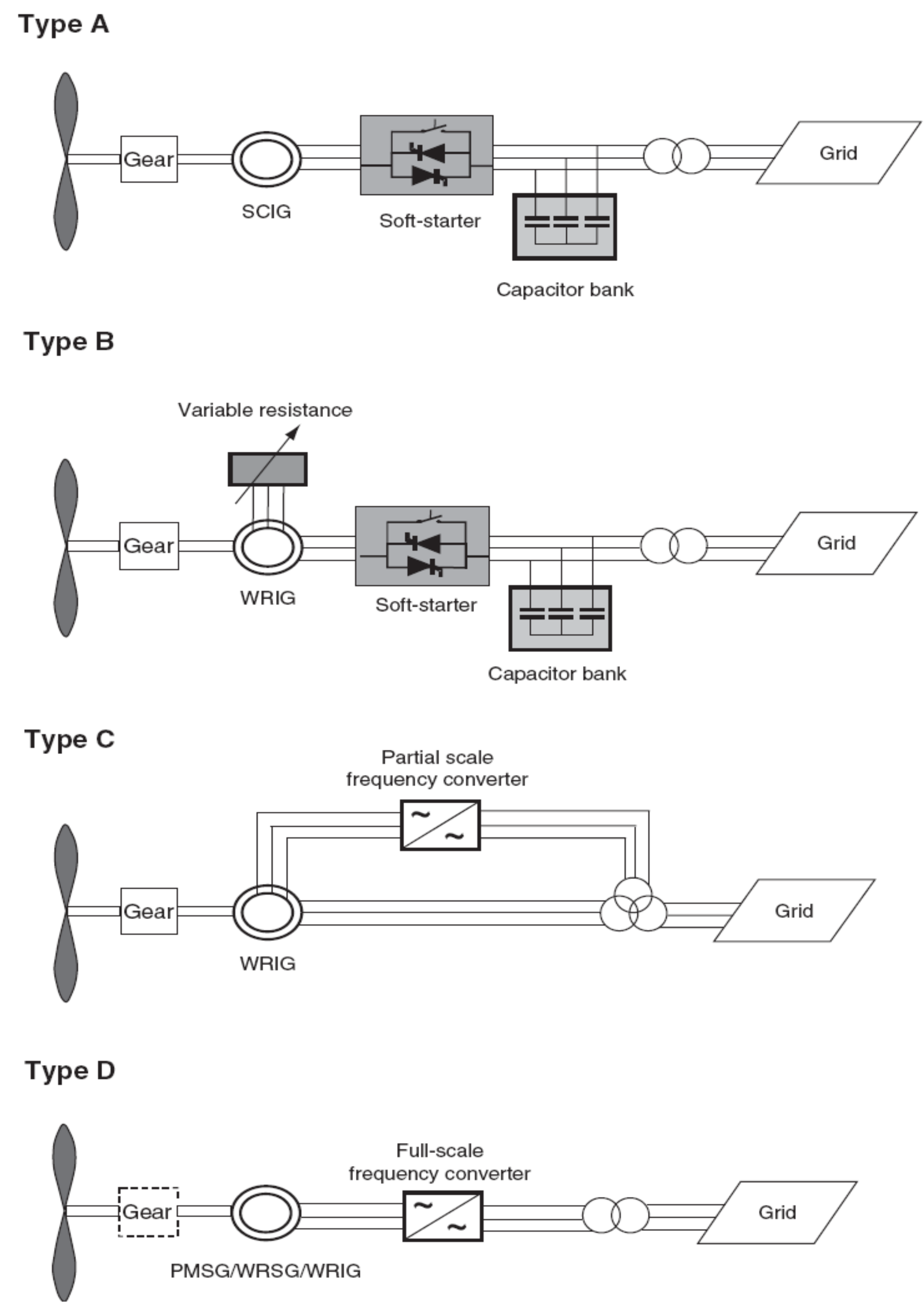
$$P_{\mathrm{G}} = P_{\mathrm{D}} + P_{\mathrm{L}} - P_{\mathrm{W}},$$

where:

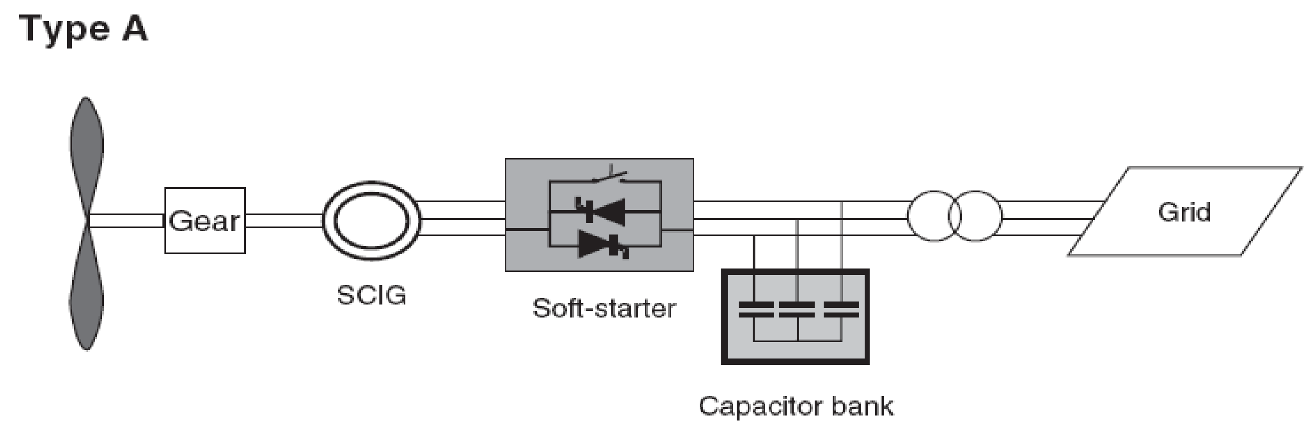
P_G	additional required power production;
P_D	power consumption;
P_L	electrical losses in the impedances Z_1–Z_3;
P_W	wind power production.

Generators and Power Electronics for Wind Turbines.

State-of-the-art Technologies



Type A: Fixed Speed Concepts



Type A0: Stall Control

the wind fluctuations are converted into mechanical fluctuations and consequently into electrical power fluctuations.

very popular because of its relatively low price, its simplicity and its robustness. Stall-controlled wind turbines cannot carry out assisted startups.

Type A1: Pitch Control

facilitates power controllability, controlled startup and emergency stopping. Its major drawback is that, at high wind speeds, even small variations in wind speed result in large variations in output power.

Type A2: Active Stall Control

This configuration basically maintains all the power quality characteristics of the stall-regulated system.

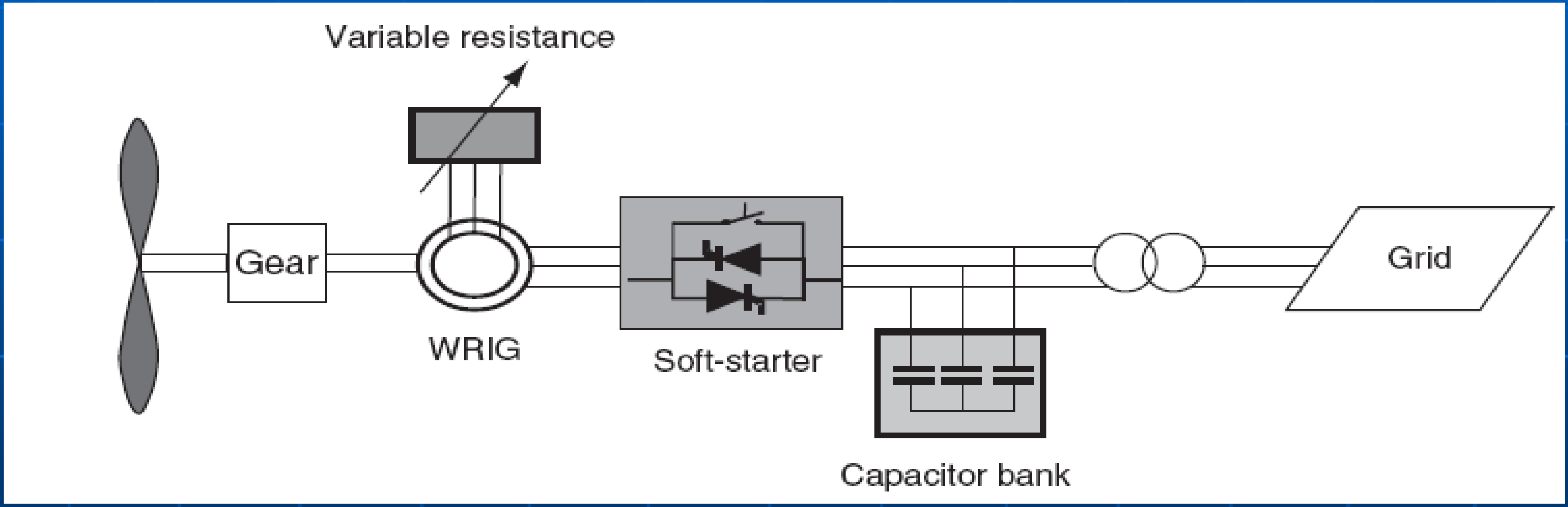
The flexible coupling of the blades to the hub also facilitates emergency stopping and startups.

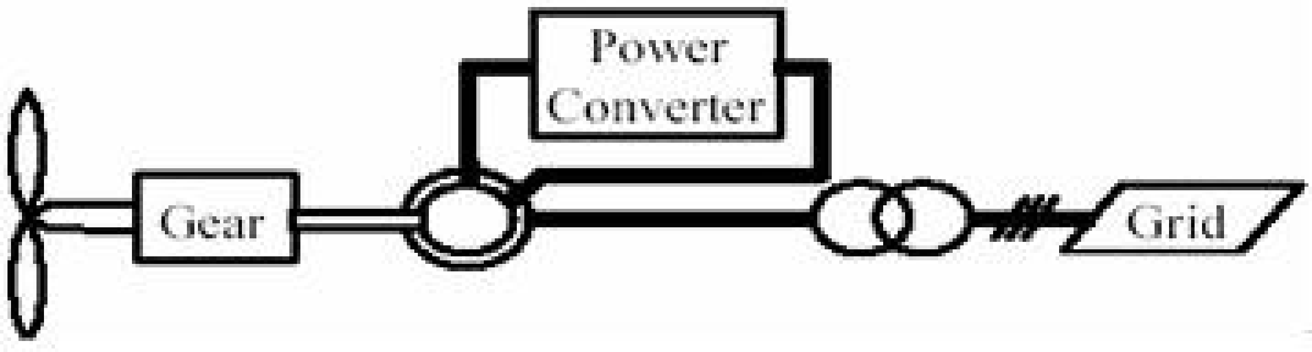
One drawback is the higher price arising from the pitching mechanism and its controller.

Variable Speed Concepts

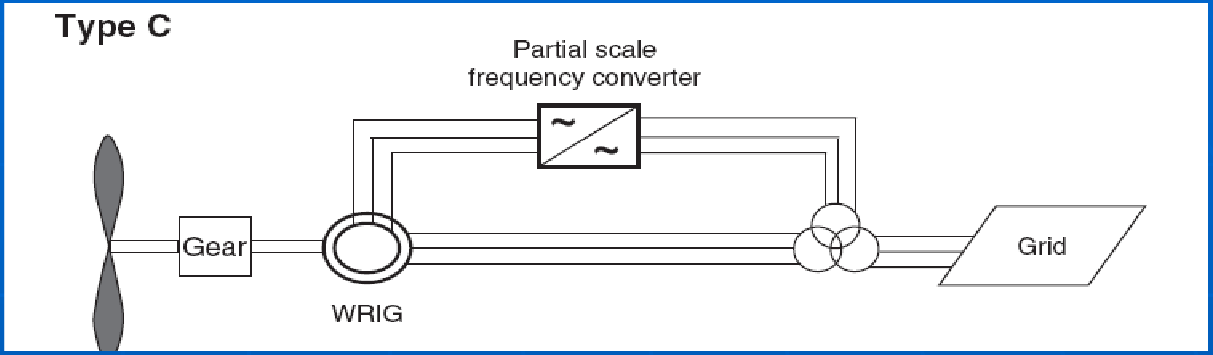
Type B: Limited Variable Speed

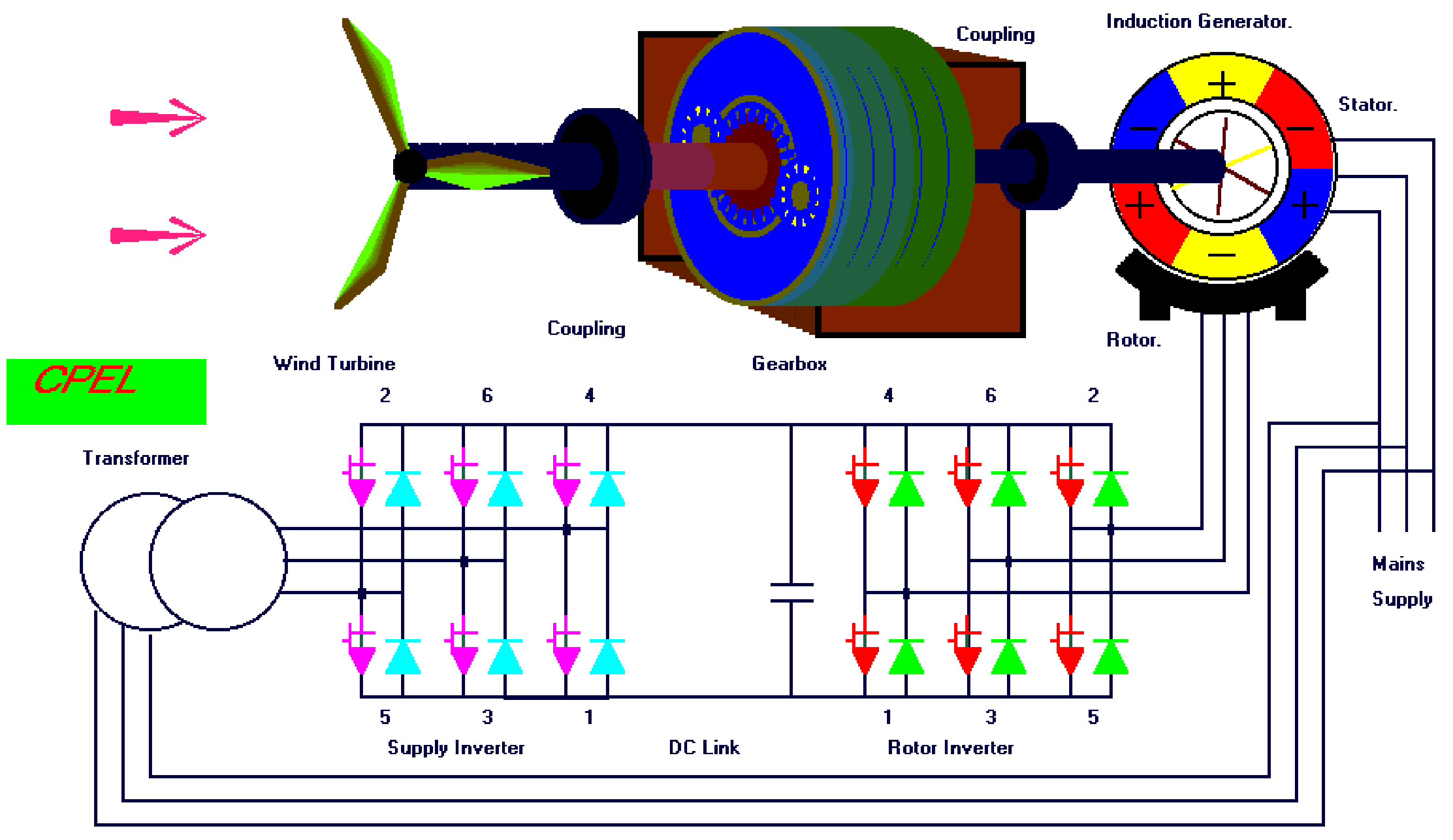
This configuration corresponds to the limited variable speed wind turbine with variable generator rotor resistance, known as OptiSlip.

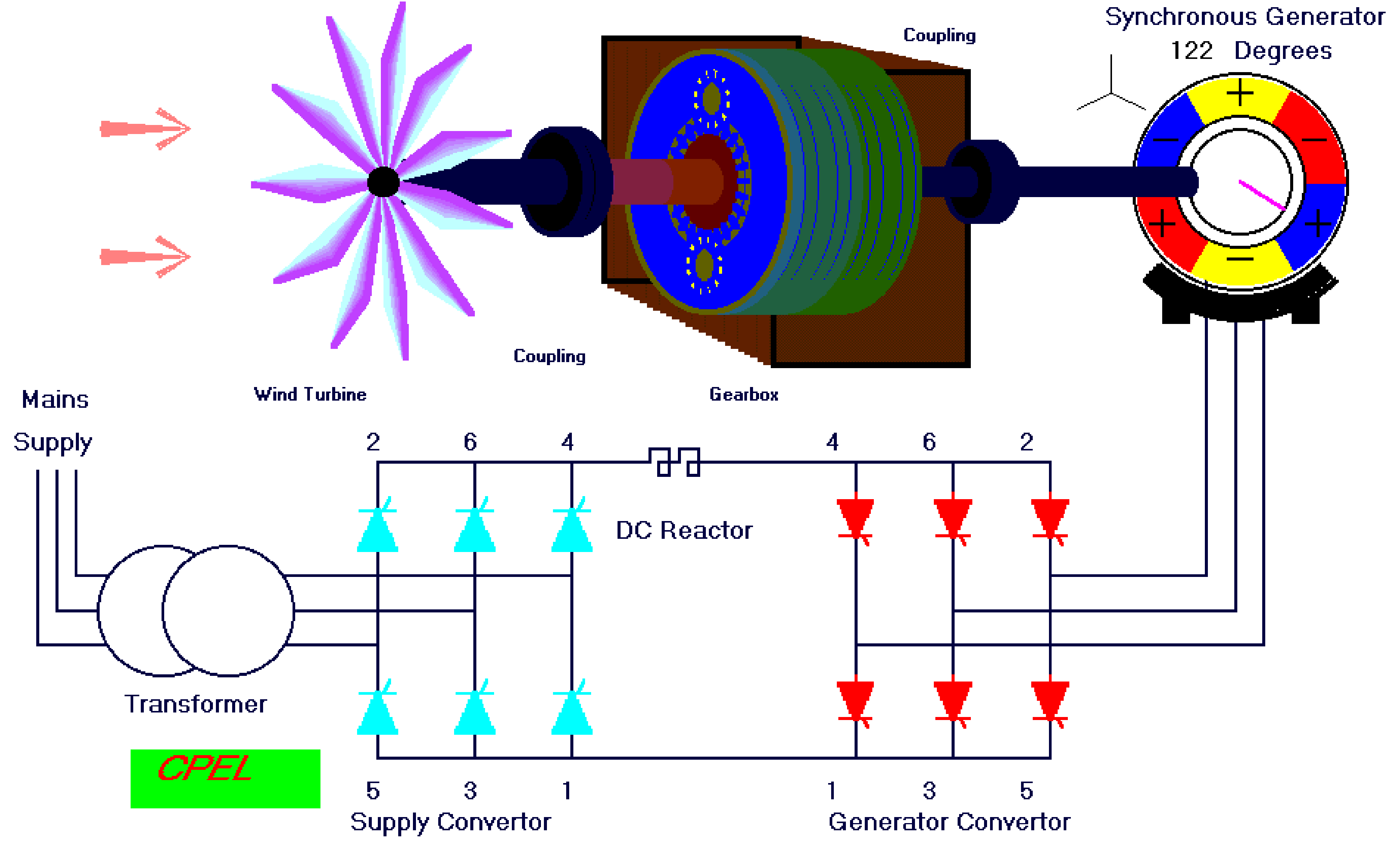




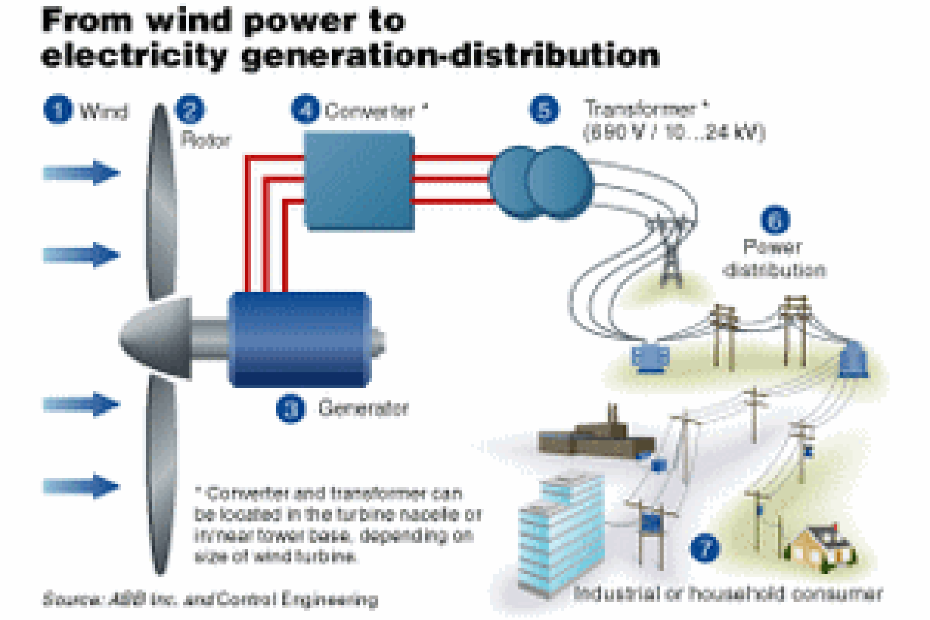
Type C: Variable Speed with Partial Scale Frequency Converter






Synchronous Generator
122 Degrees
Coupling
+
−
−
+
+
−
Coupling
Wind Turbine
Gearbox
Mains
Supply
2
6
4
DC Reactor
4
6
2
Transformer
CPEL
5
3
1
Supply Convertor
1
3
5
Generator Convertor

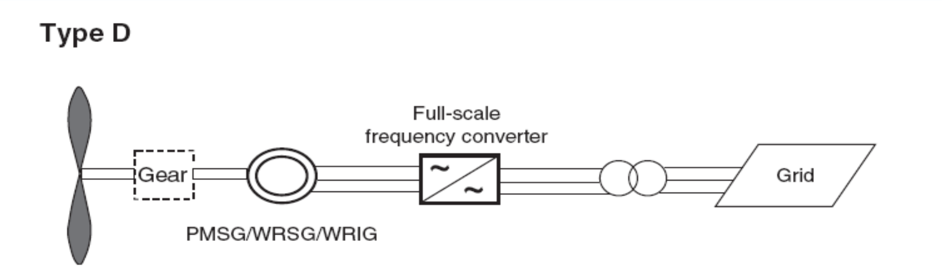
Type D: Variable Speed with Full-Scale Frequency Converter



From wind power to electricity generation-distribution

* Converter and transformer can be located in the turbine nacelle or in/near tower base, depending on size of wind turbine

Source: ABB Inc. and Control Engineering



Type D

The frequency converter performs the reactive power compensation and the smoother grid connection.

The generator can be excited electrically as in case of WRSG or WRIG) or by a permanent magnet

State-of-the-art Power Electronics

Power electronics have two strong features:

Controllable frequency:

the following direct benefits to wind turbines:

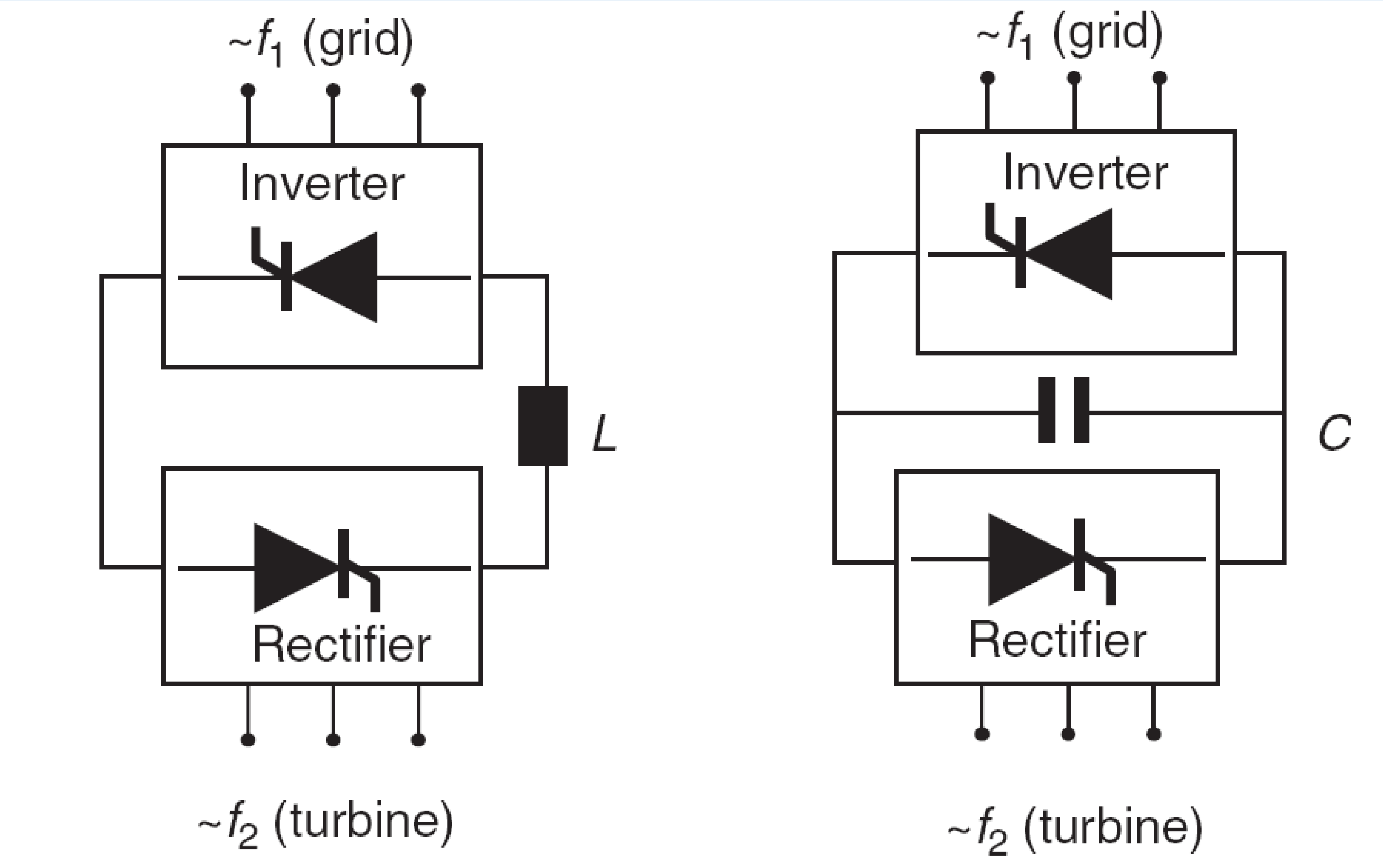
(1) optimal energy operation; (2) reduced loads on the gear and drive train, as wind speed variations are absorbed by rotor speed changes; (3) load control, as life-consuming loads can be avoided; (4) a practical solution for gearless wind turbines, as the power converter acts as an electrical gearbox; and (5) reduced noise emission at low wind speeds.

Power plant characteristics:

(1) the active or reactive power flow of a wind farm is controllable; (2) the power converter in a wind farm can be used as a local reactive power source (e.g. in the case of weak grids); (3) the wind farm has a positive influence on network stability; and (4) power converters improve the wind farm’s power quality by reducing the flicker level as they filter out the low harmonics and limit the short-circuit power.

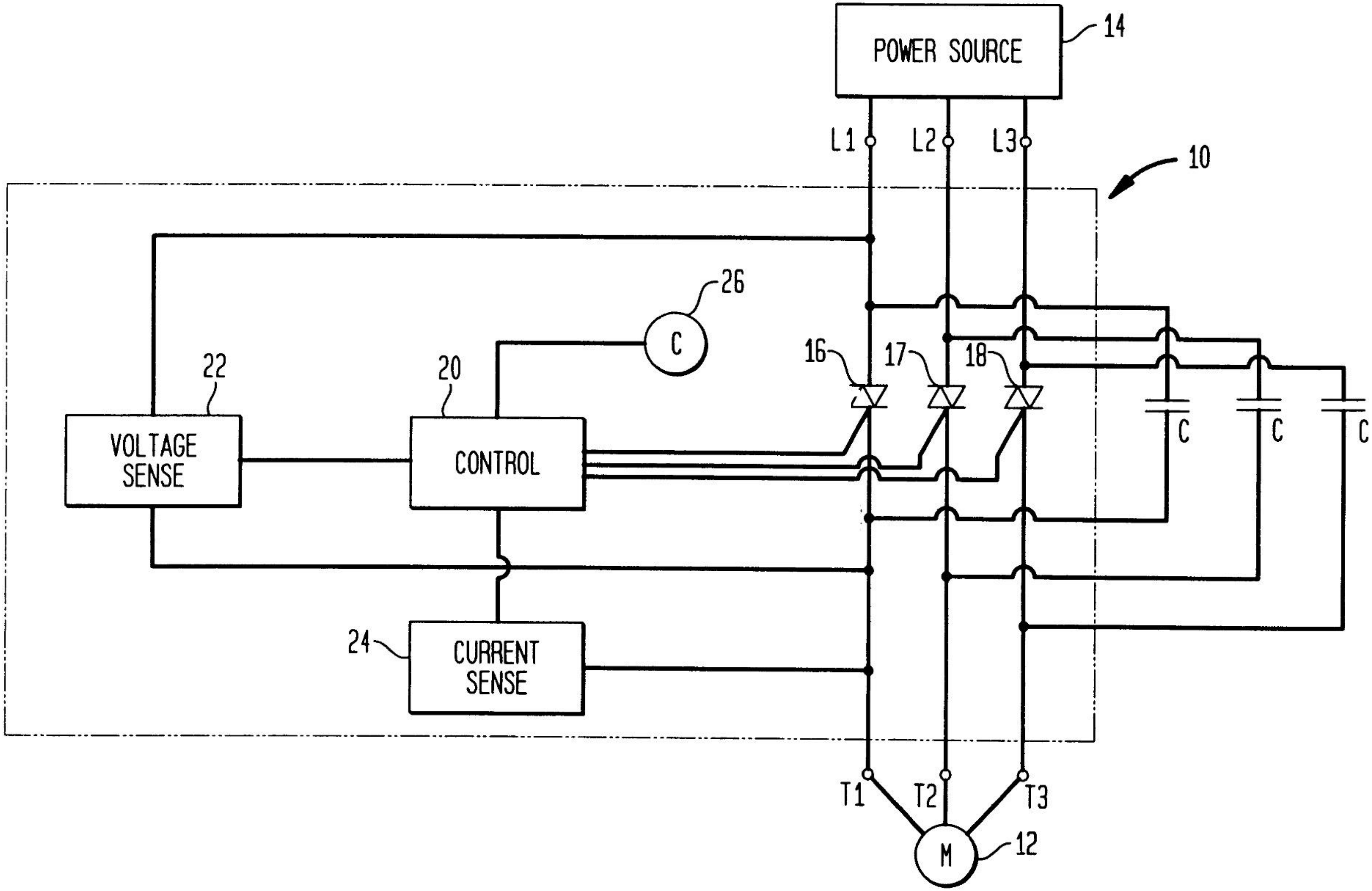
Table (3.2) Advantages and disadvantages of using power electronics in wind turbine systems

Power electronics properties	Advantages	Disadvantages
Controllable frequency (important for the wind turbine)	• Energy optimal operation • Soft drive train • Load control • Gearless option • Reduced noise	Extra costs Additional losses
Power plant characteristics (important for the grid)	• Controllable active and reactive power • Local reactive power source • Improved network (voltage) stability • Improved power quality ➢ reduced flicker level ➢ filtered out low harmonics ➢ limited short circuit power	High harmonics



Types of self-commutated power converters for wind turbines

Soft-Starter



Rectifiers and Inverters

A traditional frequency converter consists of:

- a rectifier (as AC-to-DC conversion unit) to convert alternating current into direct current, while the energy flows into the DC system; . energy storage (capacitors);
- an inverter (DC-to-AC with controllable frequency and voltage) to convert direct current into alternating current, while the energy flows to the AC side.

Frequency Converters

can be applied in wind turbines:

. back-to-back converters;

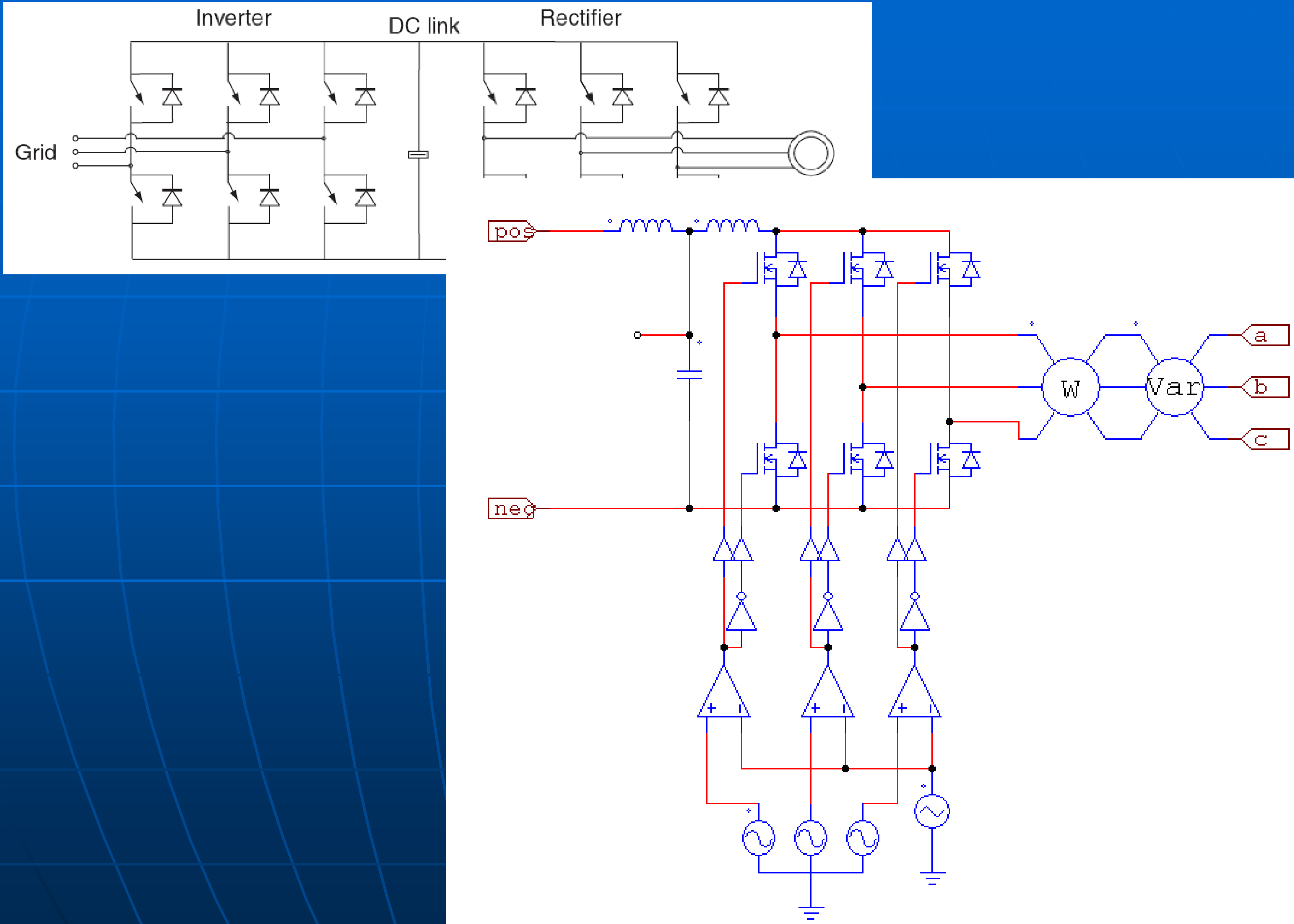
. multilevel converters;

. tandem converters;

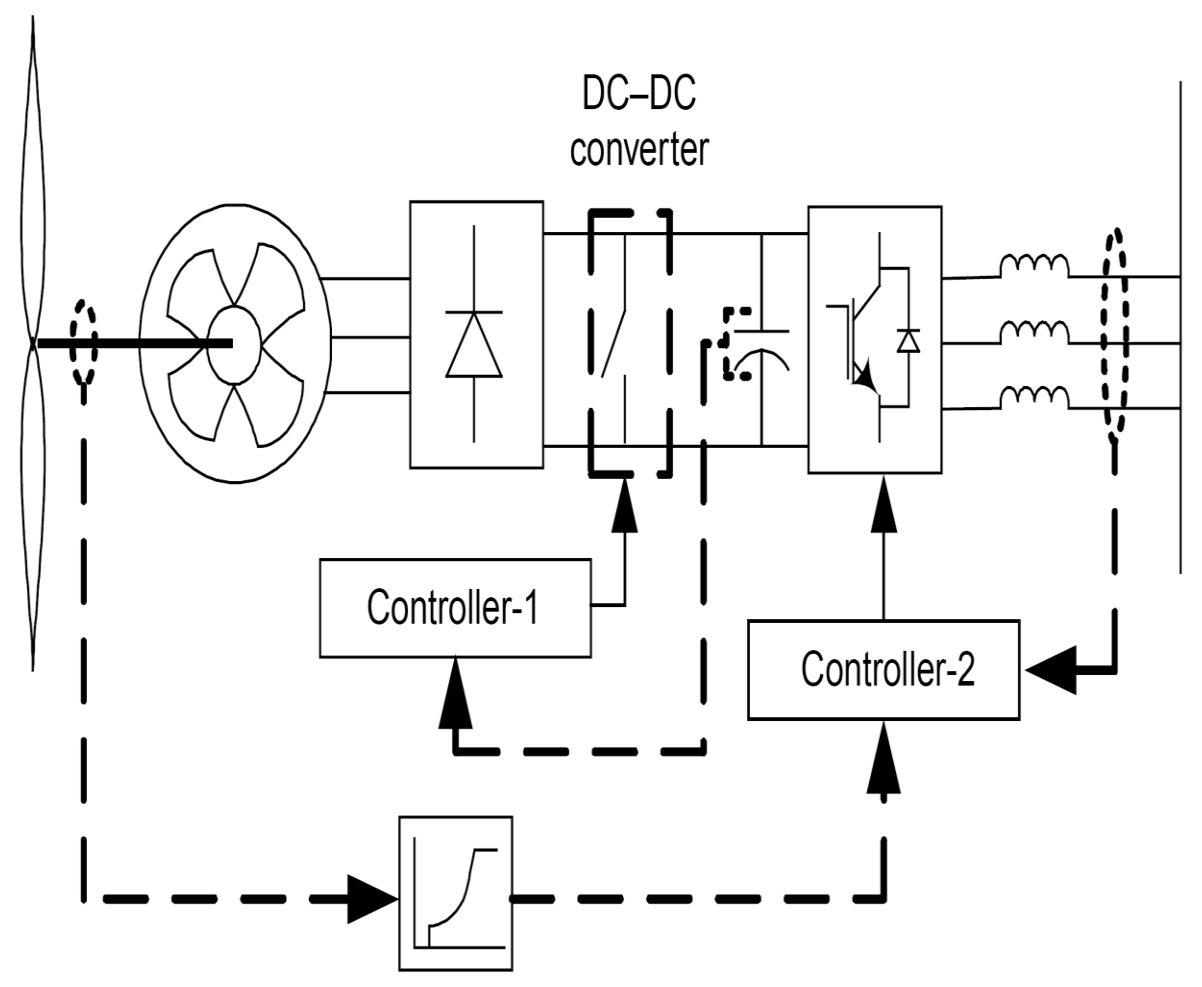
. matrix converters;

. resonant converters.

back-to-back converters



3.3.6.2 Wind Turbine Arrangement with PWM-VSCs



Pulse Width Modulation

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{tri}} = \frac{\hat{V}_{LL}}{V_{d,out}}$$

$$m_f = \frac{f_s}{f_1}$$

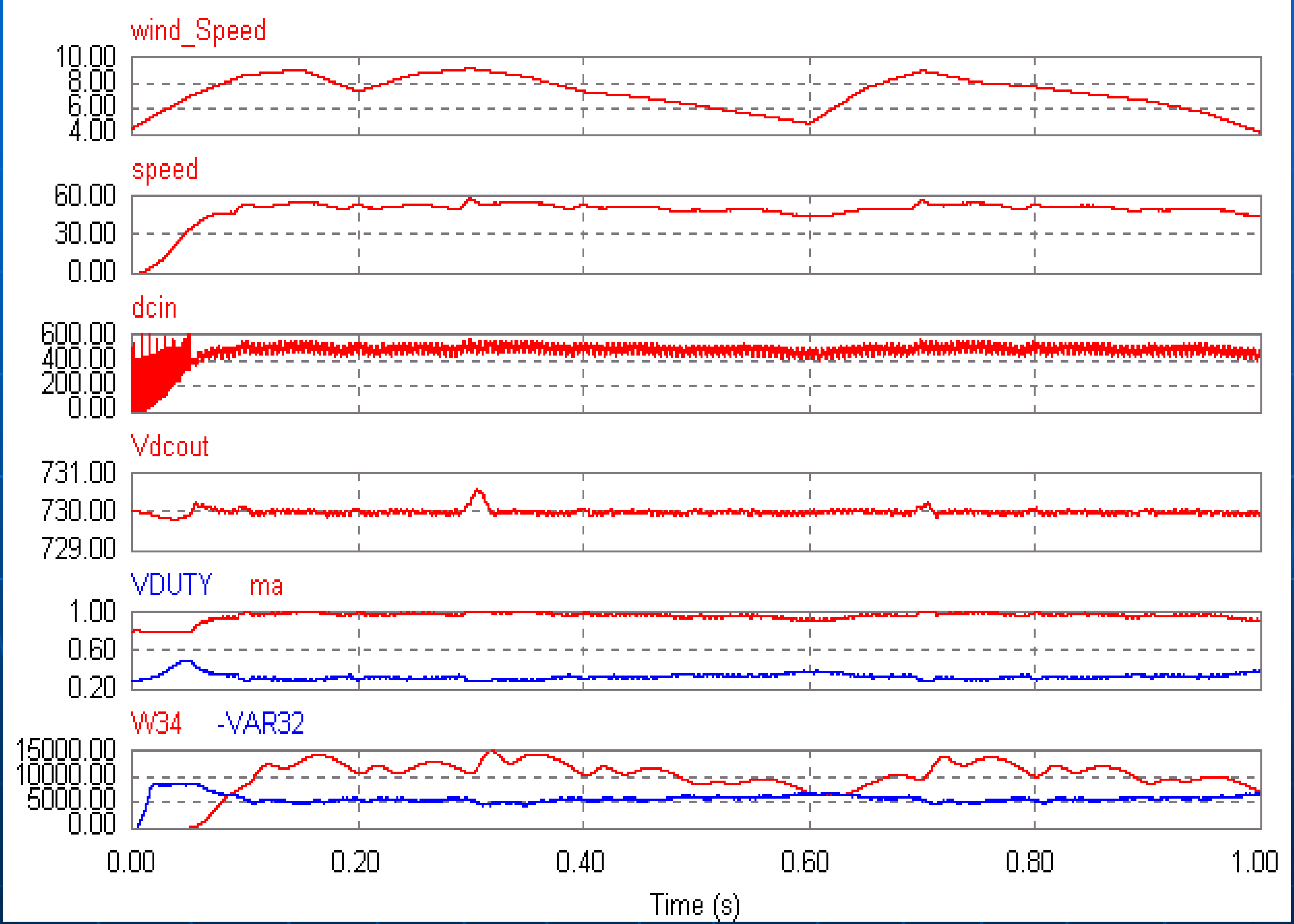
$$P_{out} = \frac{\sqrt{3}}{2\sqrt{2}} * \frac{V_{LL} * V_{d,out} * m_a * \sin\delta}{X_{UG}}$$

$$Q_{out} = \frac{\sqrt{3}\, m_a V_d}{2\sqrt{2}} * \frac{\sqrt{3}\, m_a V_d / 2\sqrt{2} - V_{LL} * \cos\delta}{X_{UG}}$$

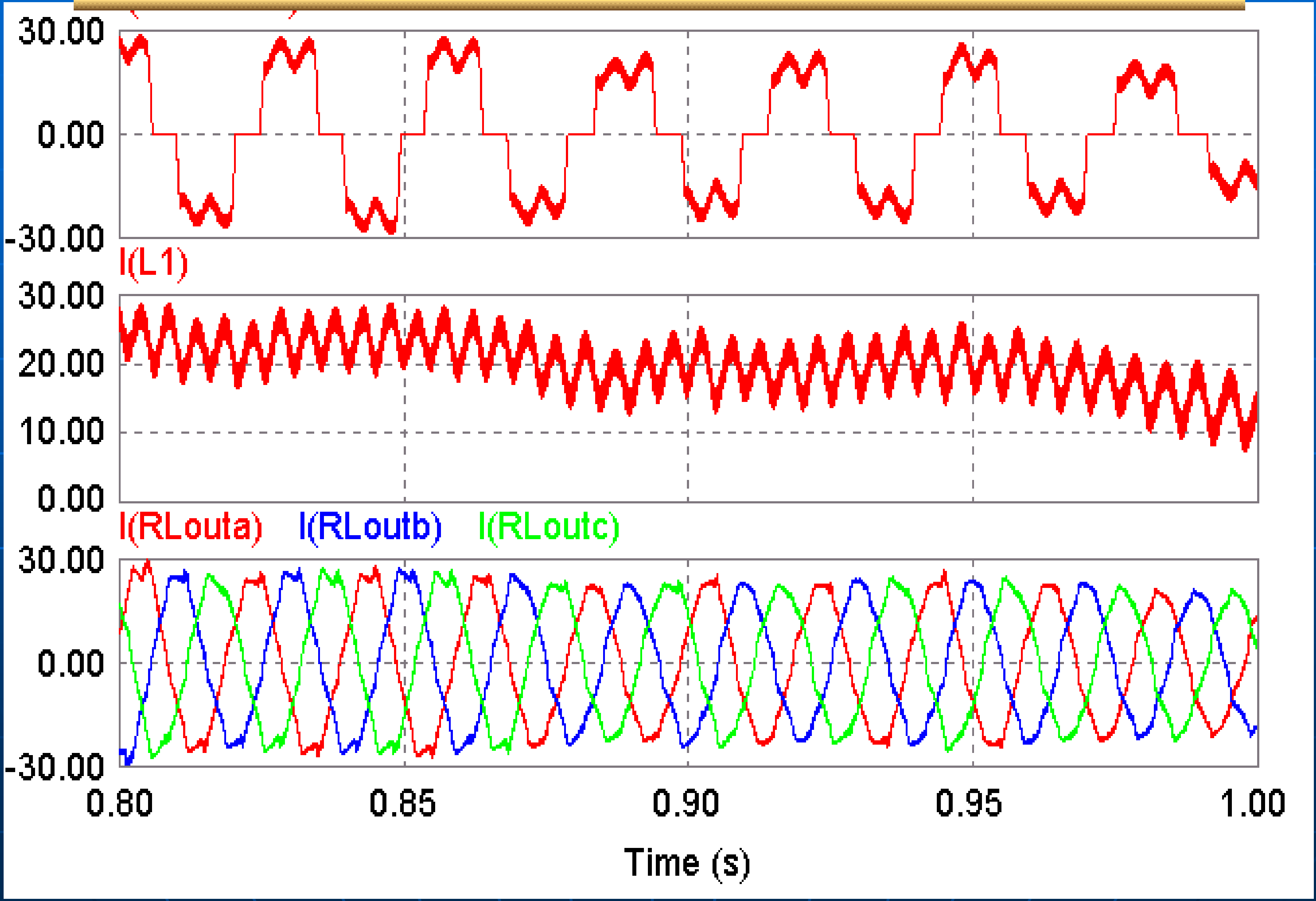
If $V_{d,out} > 730$ **Increase** m_a **Decrease** D

If $V_{d,out} < 730$ **Decrease** m_a **Increase** D

Simulation Results

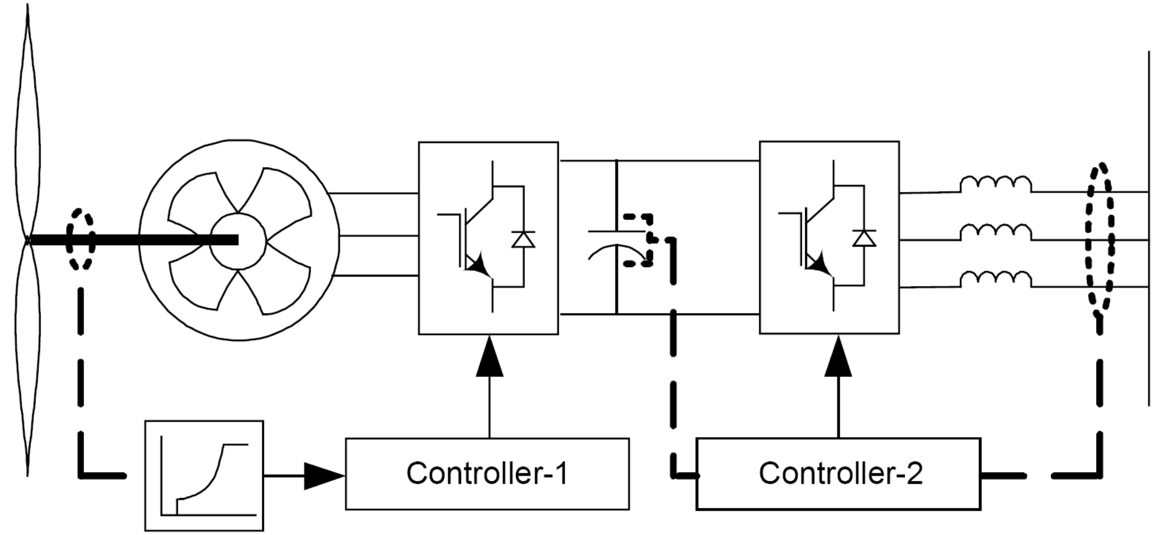


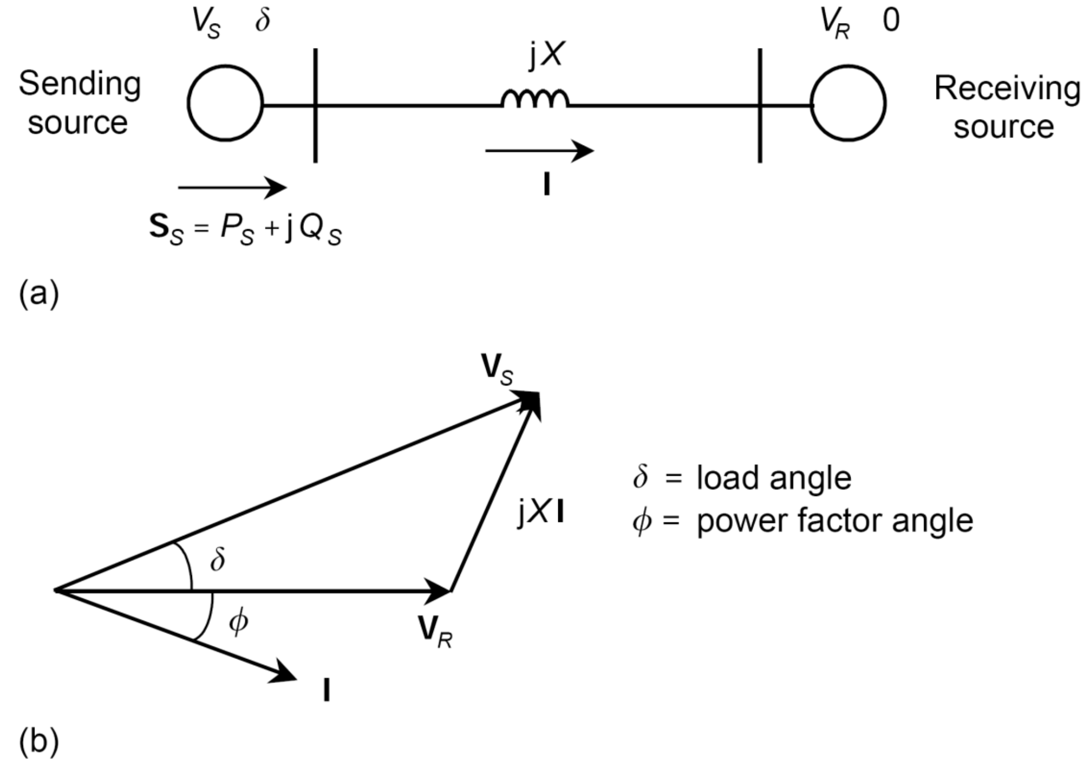
Simulation Results



- The proposed system does not need self excitation capacitors.
- The proposed system does not need gear box as when using induction generators.
- The above two points translated to reduction in the cost, increasing in the efficiency and reliability and reduce the weight on the nacelle of the WTG.
- The proposed system utilizes the maximum available power in the wind by forcing the WTG to rotate around the maximum coefficient of performance.
- The proposed controller has a stable operation for different wind speed.
- The electrical utility line currents have a very low THD.
- Simulation results show the superior stable control and high efficiency system.

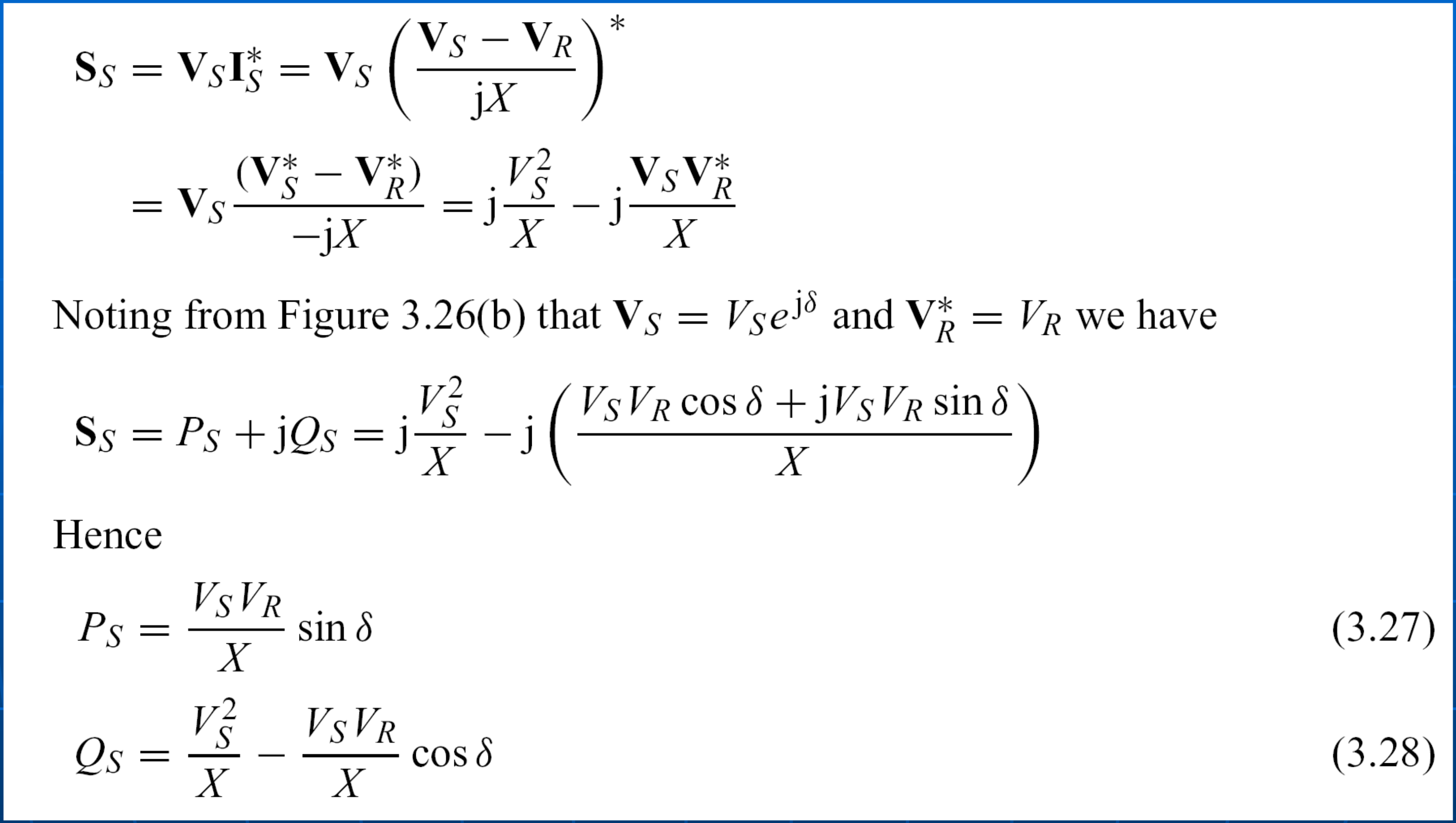
Load angle control





δ = load angle

ϕ = power factor angle



$$\mathbf{S}_S = \mathbf{V}_S \mathbf{I}_S^* = \mathbf{V}_S \left(\frac{\mathbf{V}_S - \mathbf{V}_R}{\mathrm{j}X} \right)^*$$

$$= \mathbf{V}_S \frac{(\mathbf{V}_S^* - \mathbf{V}_R^*)}{-\mathrm{j}X} = \mathrm{j}\frac{V_S^2}{X} - \mathrm{j}\frac{\mathbf{V}_S \mathbf{V}_R^*}{X}$$

Noting from Figure 3.26(b) that $\mathbf{V}_S = V_S e^{\mathrm{j}\delta}$ and $\mathbf{V}_R^* = V_R$ we have

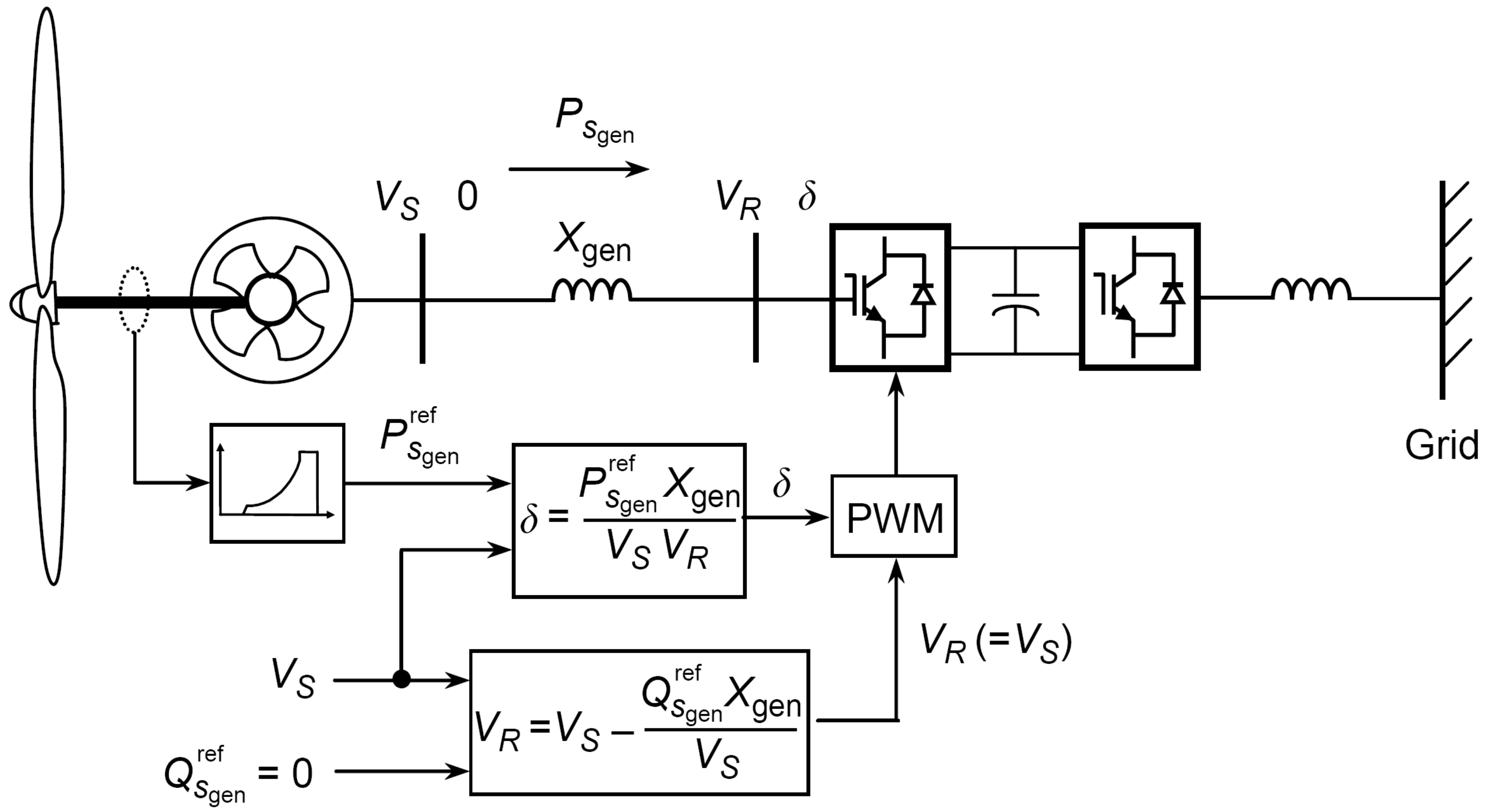
$$\mathbf{S}_S = P_S + \mathrm{j}Q_S = \mathrm{j}\frac{V_S^2}{X} - \mathrm{j}\left(\frac{V_S V_R \cos\delta + \mathrm{j} V_S V_R \sin\delta}{X} \right)$$

Hence

$$P_S = \frac{V_S V_R}{X} \sin\delta \qquad (3.27)$$

$$Q_S = \frac{V_S^2}{X} - \frac{V_S V_R}{X} \cos\delta \qquad (3.28)$$

Control of the Generator-Side Converter



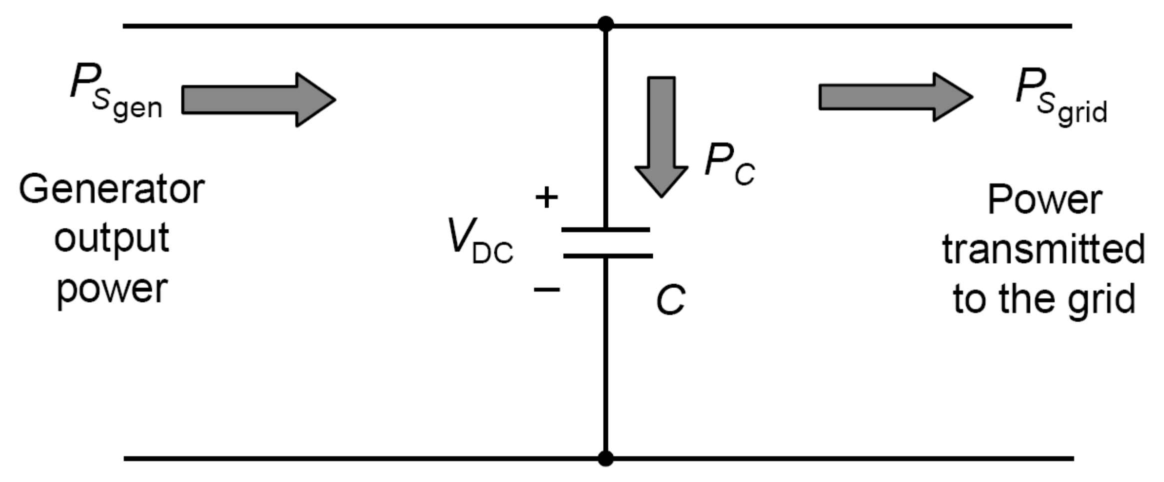
$$\delta = \frac{P_{S_{gen}}^{ref} X_{gen}}{V_S V_R} \tag{3.31}$$

$$V_R = V_S - \frac{Q_{S_{gen}}^{ref} X_{gen}}{V_S} \tag{3.32}$$

Control of the Grid-Side Converter

$$P_C = P_{Sgen} - P_{Sgrid}$$

$$P_C = V_{DC}\, I_{DC}$$



$$= V_{\mathrm{DC}} \cdot C \frac{\mathrm{d}V_{\mathrm{DC}}}{\mathrm{d}t} \qquad (3.38)$$

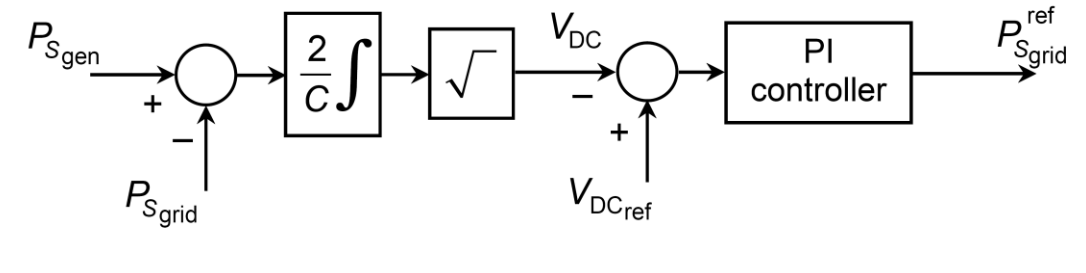
$$P_C = V_{\mathrm{DC}} \cdot C \frac{\mathrm{d}V_{\mathrm{DC}}}{\mathrm{d}t} = \frac{C}{2} \cdot 2 \cdot V_{\mathrm{DC}} \frac{\mathrm{d}V_{\mathrm{DC}}}{\mathrm{d}t}$$
$$= \frac{C}{2} \cdot \frac{\mathrm{d}V_{\mathrm{DC}}^2}{\mathrm{d}t} \qquad (3.39)$$

$$V_{\mathrm{DC}}^2 = \frac{2}{C} \int P_C \mathrm{d}t \qquad (3.40)$$

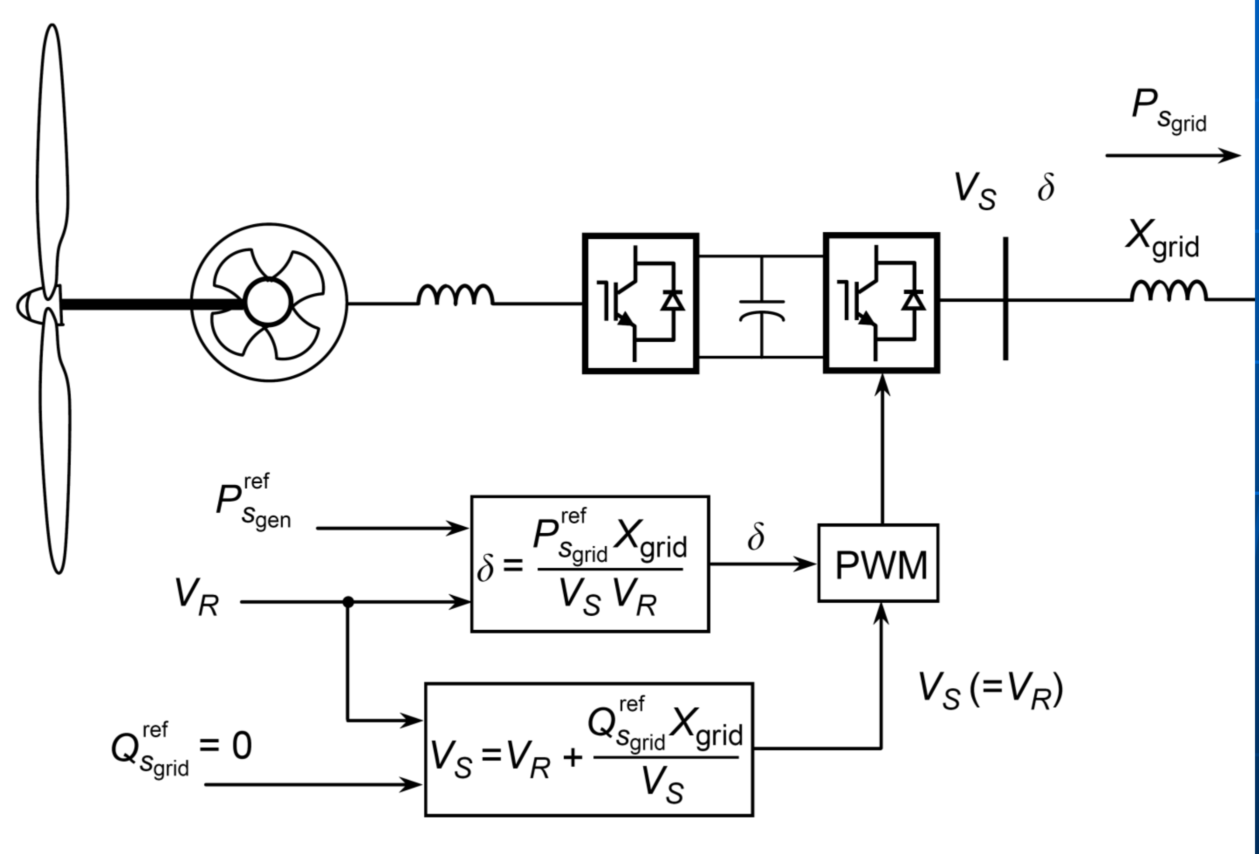
giving

$$V_{\mathrm{DC}} = \sqrt{\frac{2}{C} \int P_C \mathrm{d}t} \qquad (3.41)$$

$$V_{\mathrm{DC}} = \sqrt{\frac{2}{C} \int (P_{S_{\mathrm{gen}}} - P_{S_{\mathrm{grid}}}) \mathrm{d}t} \qquad (3.42)$$



Calculation of active power reference, $p^{ref}_{S_{grid}}$



Load angle control of the grid-side converter.

$$\delta = \frac{P_{S_{\text{grid}}}^{\text{ref}} X_{\text{grid}}}{V_S V_R} \tag{3.43}$$

$$V_S = V_R + \frac{Q_{S_{\text{grid}}}^{\text{ref}} X_{\text{grid}}}{V_S}, \quad Q_{S_{\text{grid}}}^{\text{ref}} = 0 \tag{3.44}$$

Generator Concepts

Several generic types of generators may be used in WES:

Asynchronous (induction) generator:
squirrel cage induction generator (SCIG);
wound rotor induction generator (WRIG):
OptiSlip induction generator (OSIG),
Doubly-fed induction generator (DFIG).
Synchronous generator:
Wound rotor generator (WRSG);
Permanent magnet generator (PMSG).
Other types of potential interest:
High-voltage generator (HVG);
Switch reluctance generator (SRG);
Transverse flux generator (TFG).