WIND GENERATORS

UNIT-IV

- Modeling of Permanent Magnet Synchronous Generators,
- Doubly Fed Induction Generators,
- Squirrel cage Induction Generators wind turbine,
- Control of Power converters for WECS

Modeling of Permanent Magnet Synchronous Generators,

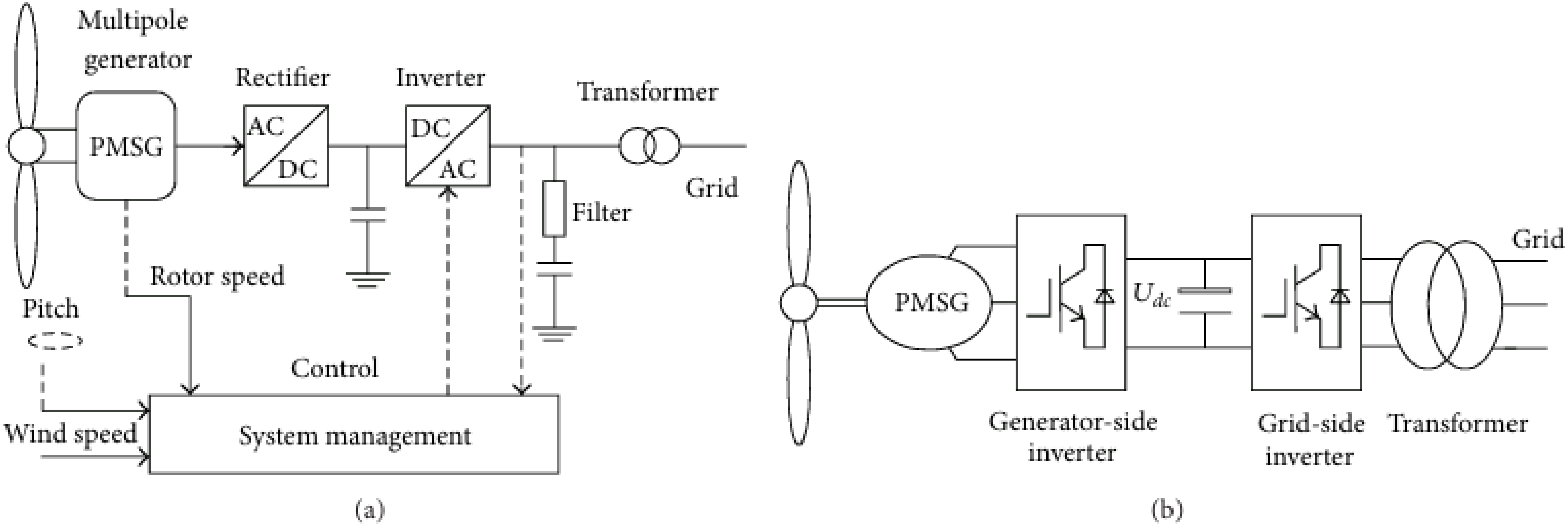


FIGURE 1: General wind turbine PMSG system with control schemes (a) and (b).

Modeling of Permanent Magnet Synchronous Generators

- Structure of PMSG Wind Turbine.
- Model of Wind Turbine.
- Model of Permanent Magnet Synchronous Generator.
- Control of PMSG Wind Turbine
    - Generator-Side Inverter Controller
    - Grid-Side Inverter Controller.
    - Pitch Angle Controller.
    - Maximum Power Point Tracking (MPPT)

Structure of PMSG Wind Turbine.

- The basic of PMSG wind turbine structure shown on Figure 1 is defined as
- T he wind turbine generates torque from wind power.
- The torque is transferred through the generator shaft to the rotor of the generator.
- The generator produces an electrical torque, and the difference between the mechanical torque from the wind turbine and the electrical torque from the generator determines whether the mechanical system accelerates, decelerates, or remains at constant speed.
- The generator is connected to a three-phase inverter which rectifies the current from the generator to charge a DC-link Udc capacitor .
- The DC-link Udc feeds a second three-phase inverter which is connected to the grid through a transformer.
- Through the control system, the information of wind speed, pitch angel, rotor RPM, and inverter output is accepted to compare with the grid-side data.
- this information is solved by using a digital signal processing to produce the correct signal to control these components.
- The main goal is to synchronize with utility grid and to export power to it.

Model of Wind Turbine.

- The wind turbine is used for the conversion of wind kinetic energy to mechanical work.
- On the basis of relationships for the calculation, it is possible to express *Pm* of the aerodynamic wind turbine power

$$P_m = 0.5 \cdot \rho \cdot A \cdot v^3 \cdot C_p(\lambda, \beta).$$

- is the air density,
- A = ΠR² is the blades swept of the turbine,
- v is wind speed, and
- Cp(, ß) is the power coefficient, which expresses the relationship between the tips peed ratio and the pitch angle ß.

T he relationship between the wind speed and the rotor speed is defined as tip speed ration λ

$$\lambda = R \cdot \omega / V,$$

where ω is the blades angular velocity and R is the rotor radius.

From the value of the rotational motion performance, itis possible to determine the value of the torque T, acting on the shaft as follow:

$$T_m = \frac{P_m}{\omega}.$$

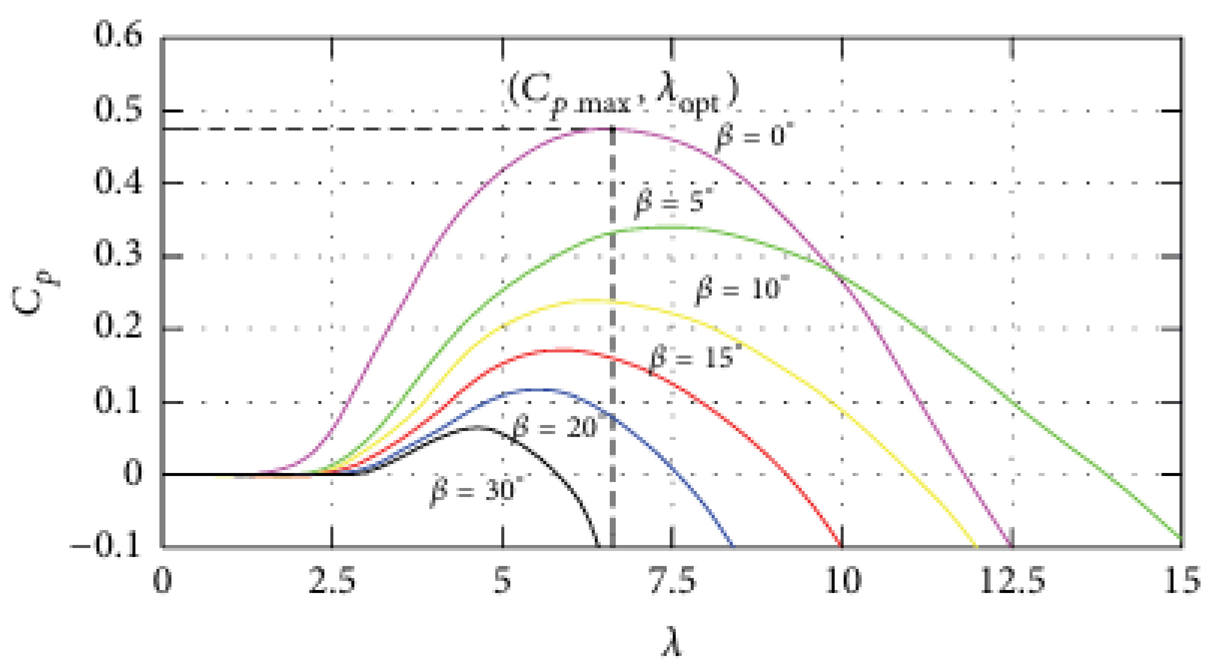


FIGURE 2: The curve of power wind turbine coefficient.

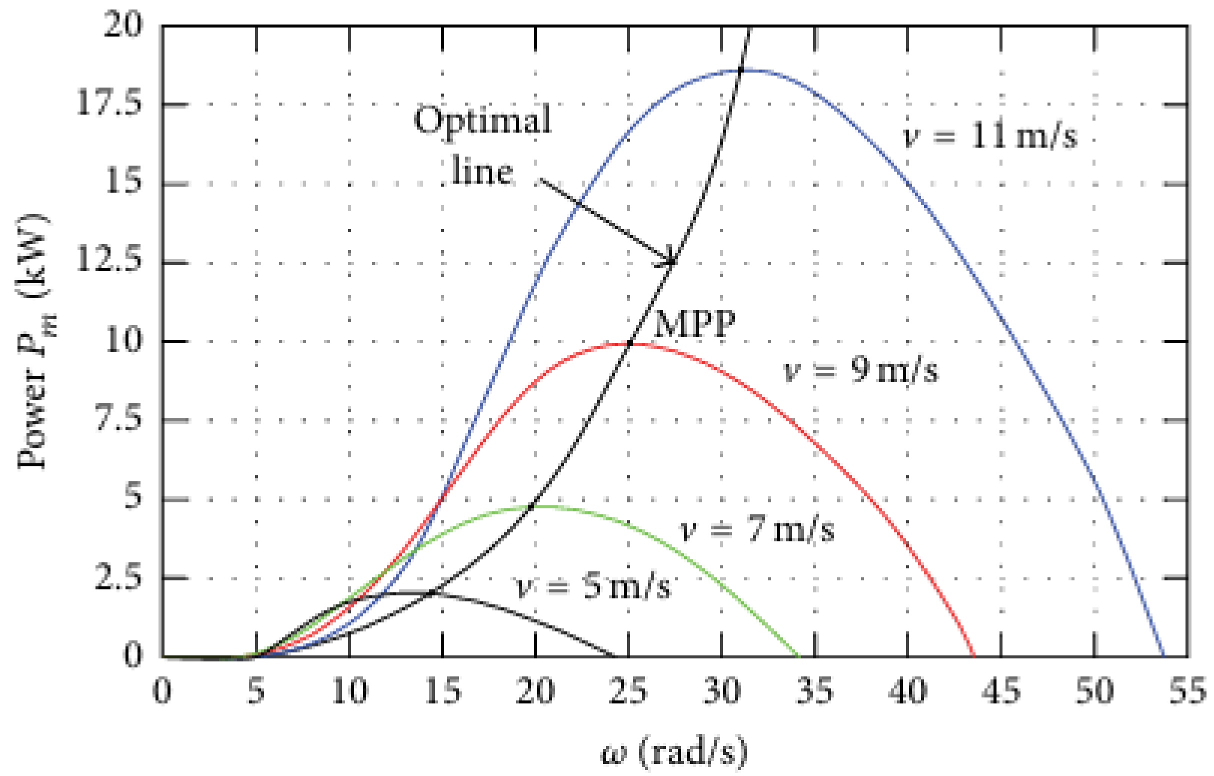


FIGURE 3: The curve to illustrate the relationship between power and wind speed.

These formulas are evident that the instantaneous values of the performance, respectively, of the mechanical torque, are dependent on the wind speed very much.

On the basis of these equations, it is possible to build the model, which structure is shown in Simulink Figure of the wind turbine .

Figure 2 shows the curve of power wind turbine coefficient.

It reveals that Cp achieves the maximum value at the particular opt.

Figure 3 shows that the rotational speed is a function, in which the power captured in turbine blade obtains the maximum output at the particular rotational speed, while the pitch angle is constant.

Hence, A should be kept at opt to maximize the wind energy.

In Figure 4, f(u) of Lambda, Gama, and Cp are defined in the order of equations (4), (3), and (2).

If wind speed is in the range from 3 m/s to cut out 25 m/s, it is combined to form turbine torque f(u) as (1) and (5).

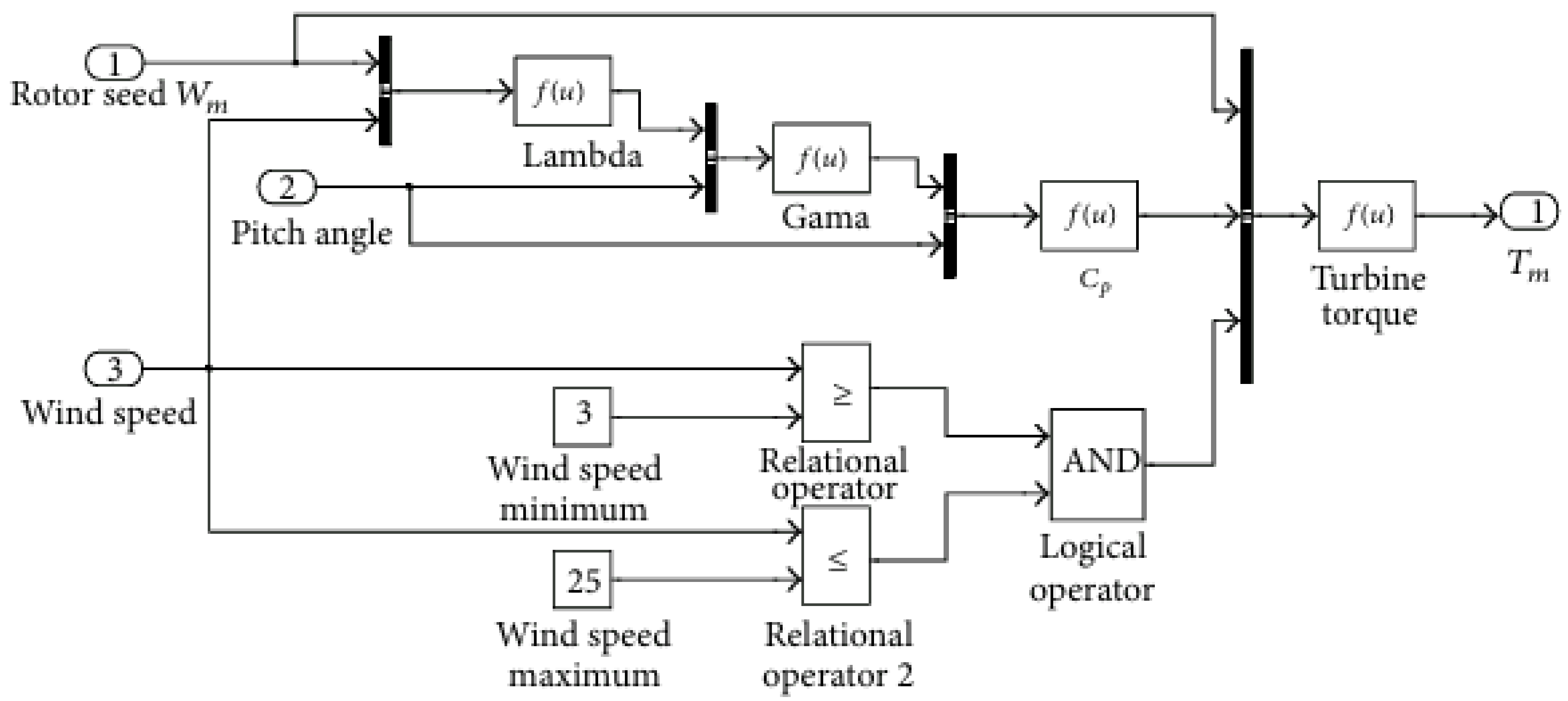


Figure 4: Model of the aerodynamic of wind turbine in Matlab Simulink 2010b.

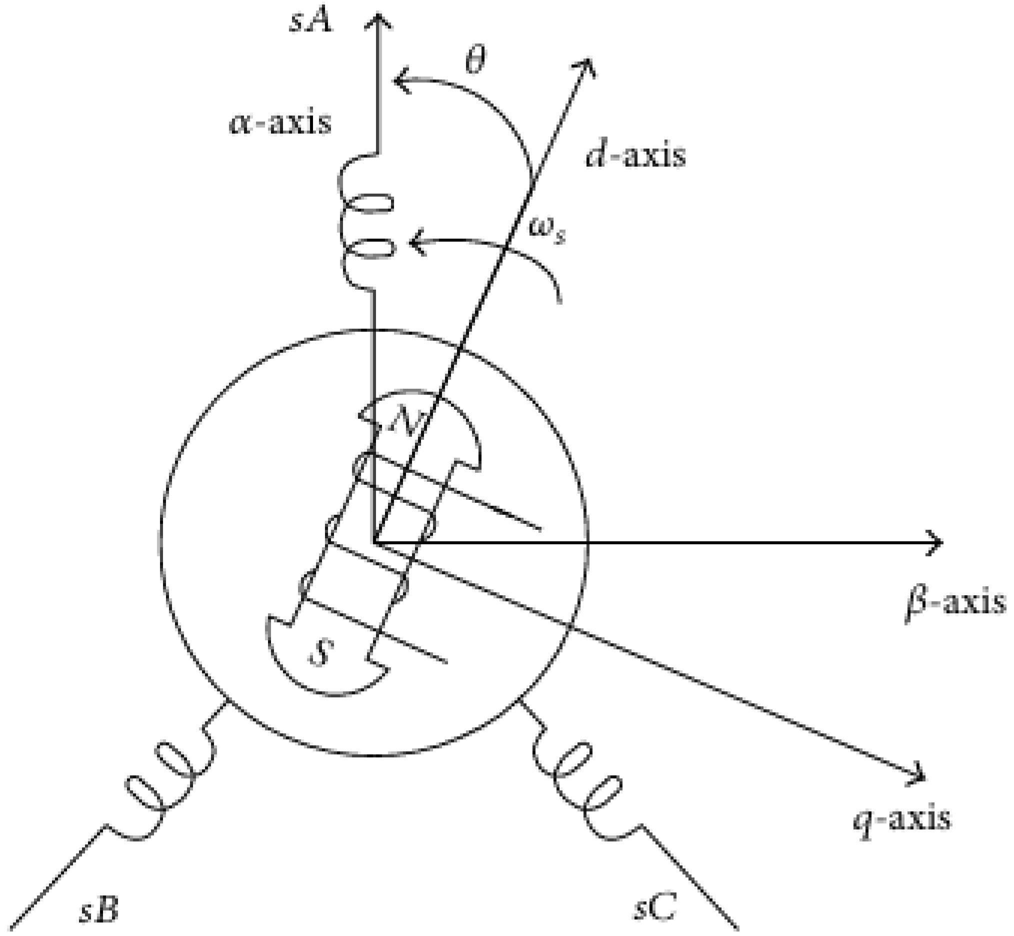


Figure 5: The dq-coordinate frame of the PMSG.

Generator-Side Inverter Controller.

- The generator-side inverter is controlled to catch maximum power from available wind power. According to (7), in order to control the electromagnetic torque Te,this study just controls the$q$-axis current $is\ q$ with the assumption that the d-axis current $is\ d$ is equal to zero.
- Further more show that,in order to catch maximum power, the optimum value of the rotation speed is adjusted.
- The tip speed ratio λ is taken in

$$\omega_{\text{ref}} = \frac{\lambda_{\text{opt}} \cdot v}{R}.$$

There, ω ref is the blades angular velocity reference and opt is the tip speed ratio optimum. From (6), it is calculated that

$$U_{sd} = R_{sa} \cdot i_{sd} - \omega_s \cdot L_{sq} \cdot i_{sq} + \frac{di_{sd}}{dt} \cdot L_{sd}$$
$$U_{sq} = R_{sa} \cdot i_{sq} + \omega_s \cdot L_{sd} \cdot i_{sd} + \frac{di_{sq}}{dt} \cdot L_{sq} + E_s, \quad (9)$$

with Es = ω s . p being the permanent flux linkages.

The generator-side inverter control schematic is illustrated in Figure 6. Through the MPPT in the error of ref is produced. Therefore, the error of ωref and ω s is rescued to PI controller to produce q-axis current component isq-ref which put into space vector pulse width modulation(SVPWM).

The d-axis current isd ref is set to zero because the d-axis current control is adopted.

Consequently, through the SVPWM containing voltage feed-forward compensation, the power factors of the generator are calculated and controlled well.

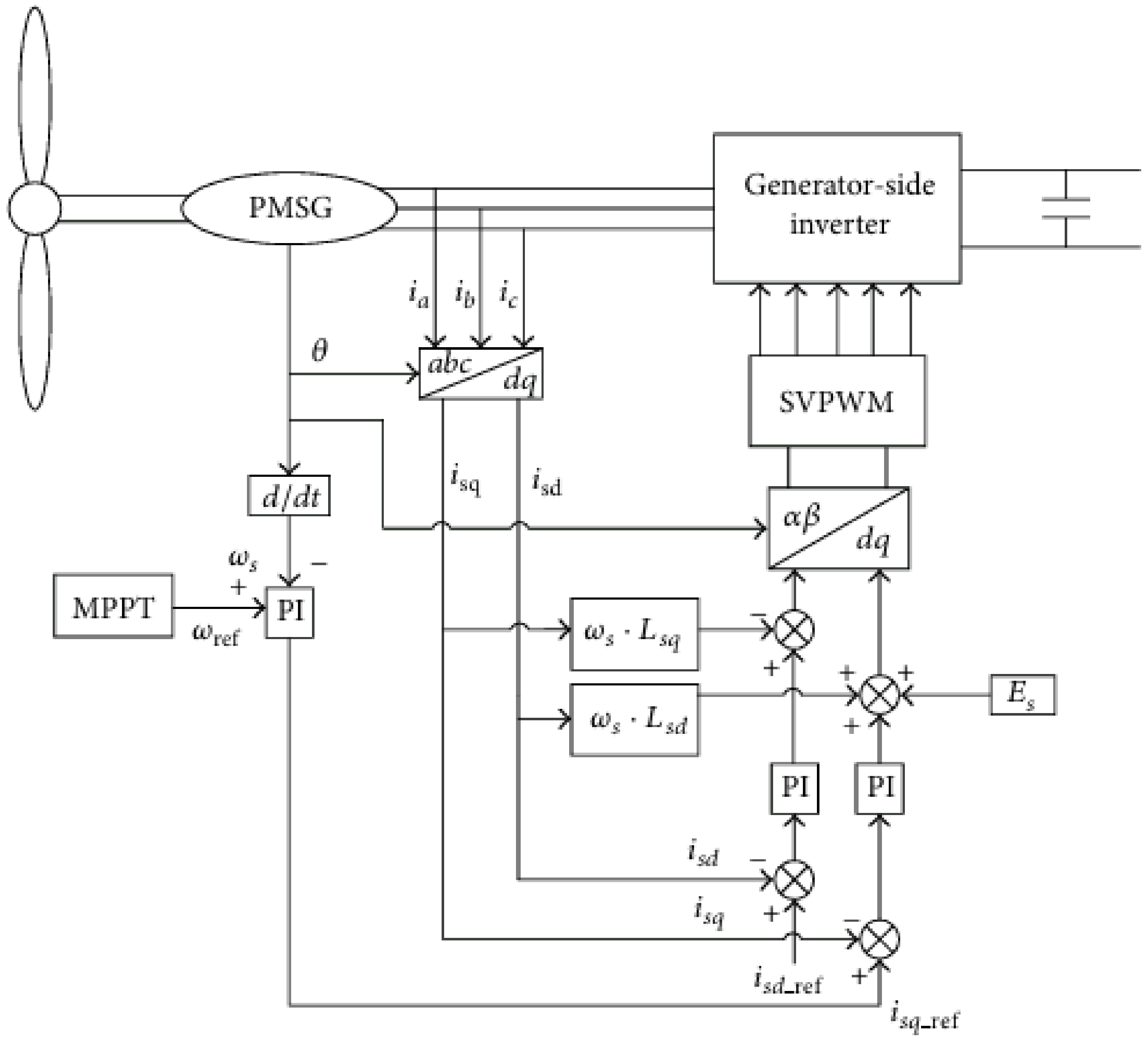


FIGURE 6: Scheme of generator-side inverter controller.

Grid-Side Inverter Controller.

- The goal of the grid-side inverter is keeping the stability of the DC-line voltage as well as controlling the active and reactive power For the grid/transformer inductance, the model is given as follows:

$$u_d = e_d - R \cdot i_d + \omega \cdot L \cdot i_q - L \cdot \frac{di_d}{dt},$$

$$u_q = -R \cdot i_q - \omega \cdot L \cdot i_d - L \cdot \frac{di_q}{dt}.$$

Here, ed is the d-axis output voltage of the grid, respectively,

ω is the angular frequency in electrical degree of grid,

R is the resistance,

L is the inductance, respectively, and id and iq are the currents of d-axis and q-axis.

it is easy to figure out that the current of d-axis and q-axis can be controlled to moderate the active and reactive power.

Grid-Side Inverter Controller.

- In Figure 7, the loop voltage and the loop current are illustrated. The inner current loop is controlled through PI controller similar to generator-side inverter controller.
- The output voltage loop produces PI controller for calculating the error between Udc and Udc-ref to produce id-ref.
- Therefore, q-axis current is set to be zero to decoupling control of the active power P and reactive power Q by moderating the d-axis current id and the q-axis current iq.

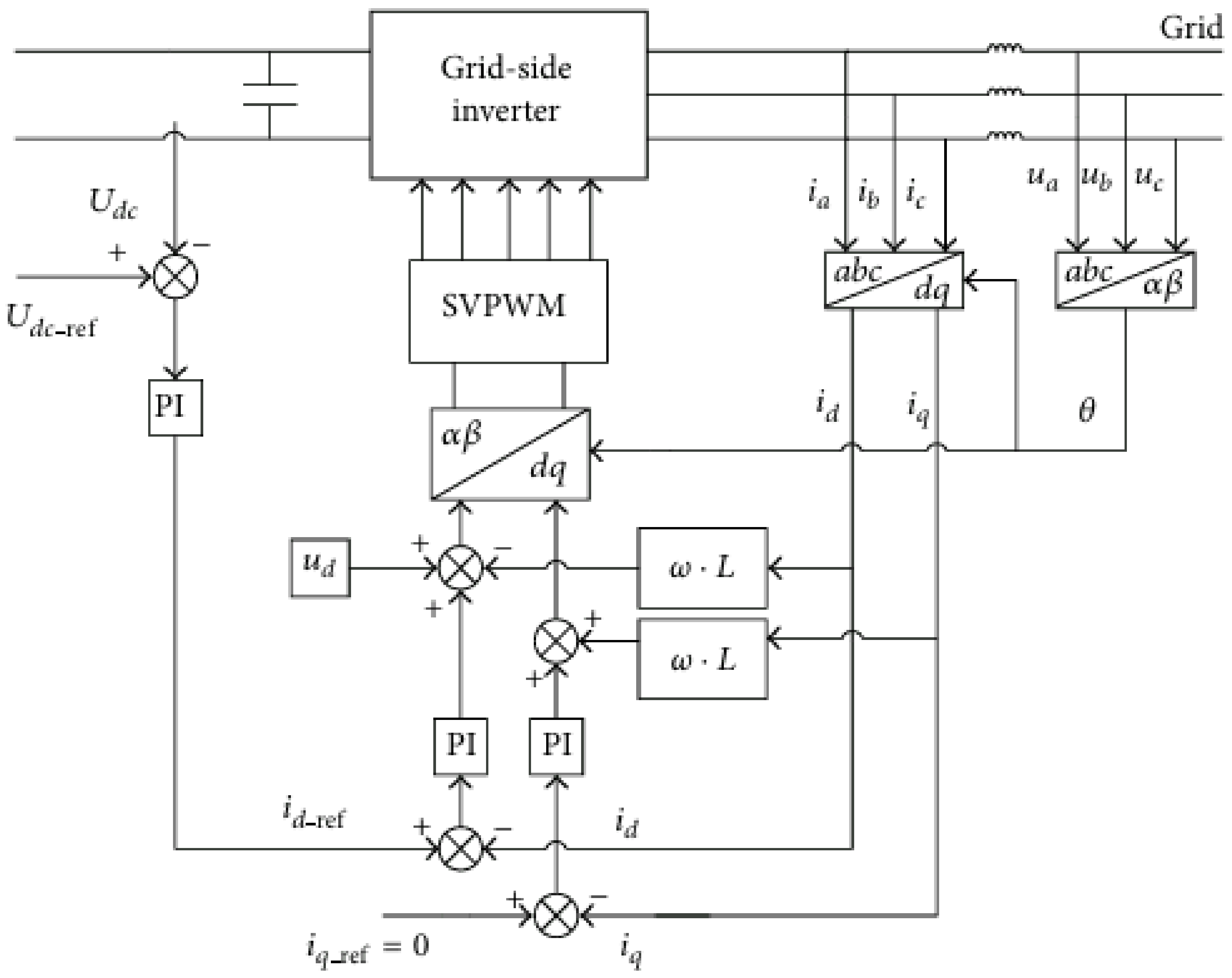


FIGURE 7: Scheme of grid-side inverter controller.

Pitch Angle Controller

- . The system of aerodynamic control plays an important role in regulating the mechanical power.
- Pitch angle controller is based on the principle which is changing the blades angle at the revolutions over the maximal generator speed as well as protecting the generator before overloading at high wind speeds.
- The optimal angle for the wind speed below the nominal value is approximately zero and then it increases with the wind speed growing.
- It has considerable impact on the performance coefficient and on the value of the turbine torque
- In this controller, illustrated in Figure 8, the speed of the generator which is the input is compared with its reference value through PI controller to have the output value of the pitch angle of the blades, which changes the performance coefficient of the turbine.

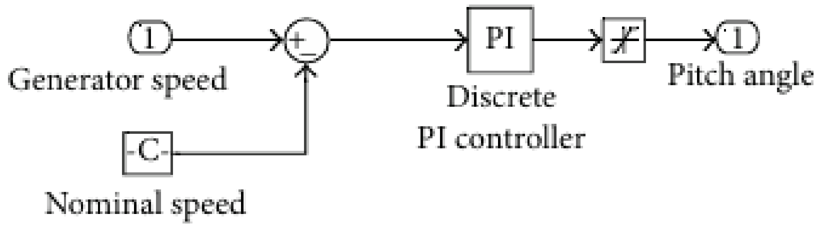


FIGURE 8: Model of pitch angle controller in Matlab Simulink 2010b.

Maximum Power Point Tracking (MPPT).

- In the generator-side inverter, MPPT produces the ωref for the (10) comparative PI controller.
- According to Figure 3 the wind turbine coefficient achieves the maximum for the tip speed, when the pitch angle β = 0.
- In terms of every wind speed, there exists a specific point to get the maximum output.
- Hence, in order to control the maximum power in every wind speed, the MPPT tracks the continuous line and optimal line in Figure 9.
- The tip speed ratio is kept at constant value for all maximum power points, while the relationship between the wind speed and the wind turbine generator speed is explained as follows

$$\Omega_n = \lambda_n \frac{V_n}{R},$$

- being the optimal rotation wind turbine generator at the wind speed V.
- The MPPT control strategy is based on monitoring the wind turbine generator output power using measurements of the wind turbine generator output voltage and current as well as directly modelling the dc/dc converter duty cycle, which is

- Model of wind turbine is in wind turbine; models of control system of generator-side inverter and grid-side inverter are included in Subsystem1 and Subsystem2.
- The MPPT controller and PI controller are also included in Subsystem 1and Subsystem2.
- The pitch angle controller is completely modelled in wind turbine.
- In this simulation, the wind turbine PMSG model obtains the wind speed and provides an optimal reference speed to control the system.
- The simulation results are shown in Figures 11–14.

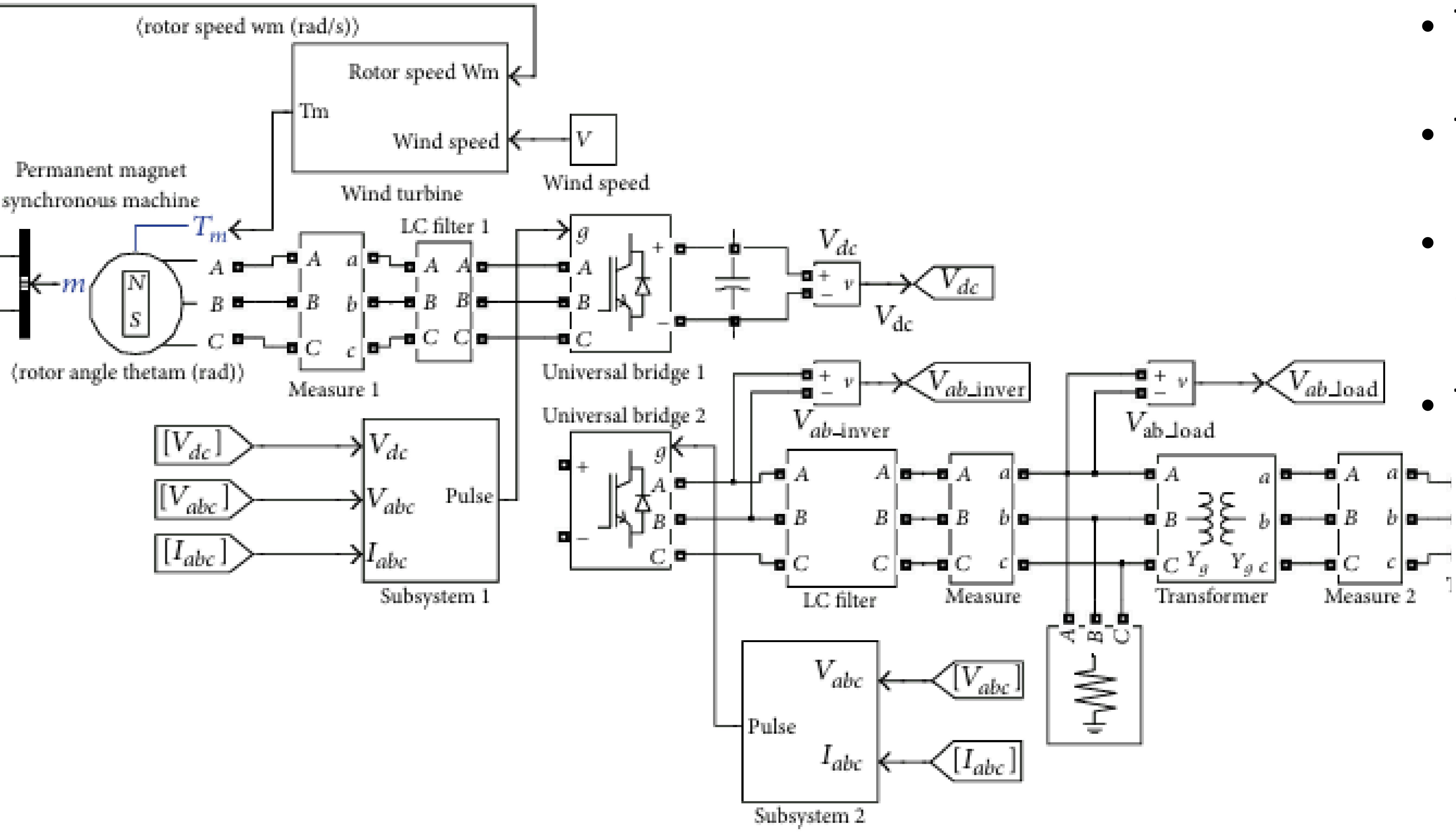


FIGURE 10: Simulation model of autonomous control PMSG wind turbine.

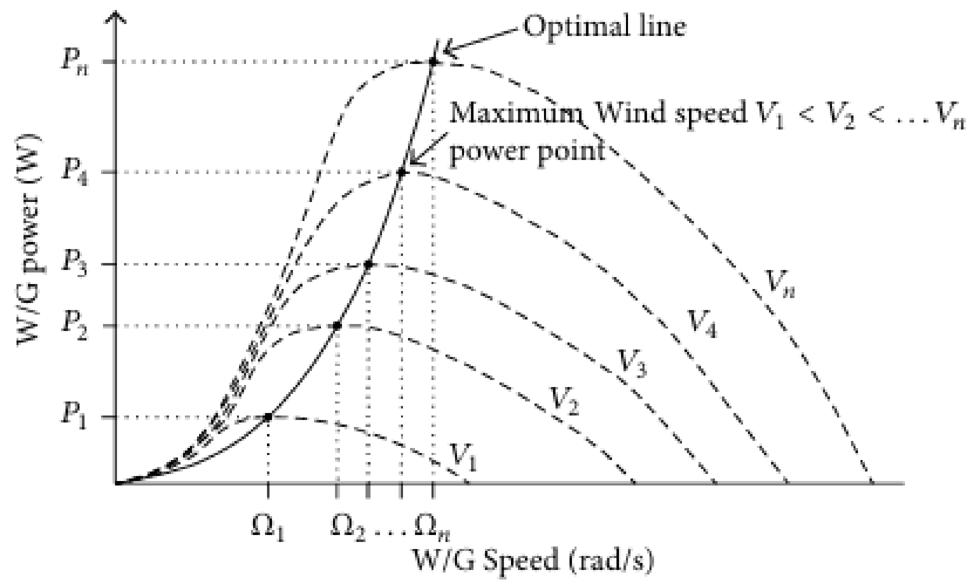


FIGURE 9: Wind turbine generator power curve at various wind speeds.

- The main system parameters are listed in Table 1 according to the design consideration.
- The original states of the system are zero.
- When wind speed is 12m/s, optimal speed of PMSG is obtained.
- Pitch angle controller catches the optimum tip speed ratio at 8 and optimum power coefficient at 0.4 through the maximum power point tracking.
- On the other hand, grid-side inverter models the output voltage with the DC-link voltage 1200V in accordance with DC link capacitor 15000μF.
- After all, PMSG wind turbine with autonomous co r 15000μF. After all, PMSG wind turbine with autonomous control system produces the grid line voltage at 900V.
- Figure 11 shows the waves of DC-link voltage, the voltage is produced by grid-side inverter and a phase voltage feeding to the grid.
- Through the results, it is admitted that DC voltage is well controlled in stabilizing performance with the fluctuation being about 25%.
- When *Vab* passes through the inverter, load voltage slightly fluctuates by the late modelling during 0s to 0.08s.
- After that, the load voltage can be kept in stable output.
- Figure 12 shows the wave forms of *d*-current, voltage phase of PMSG, and *d*-voltage reference.

- According to the results, it can be revealed that, despite the usual change of wind speed, the *d*-axis current is still modelled to be maintained at zero level off.
- The voltage phase per unit (pu) of PMSG is decreased after the beginning stage; however, it keeps constant value at that later time.
- Figure 13 shows the waves of three-phase voltage and current of the grid when autonomous PMSG wind turbine is operated at stable state.
- Voltage phase almost opposes the current phase. Figure 14 performs the waves of active power and reactive power decoupling control.
- When the wind the pitch angle is controlled to catch the maximum coefficient at rate 13m/s wind speed.
- After 0.14s, the generator-side inverter and the grid-side inverter are cooperated to control the voltage through controllers.
- The wind turbine gets the stable output power to the grid with standard voltage, frequency, and phase.
- By the autonomous control, including pitch angle con troller, generator-side inverter, and grid-side inverter, the wind turbine is able to achieve the highest efficiency.
- Through the MPPT strategy as well as pitch angle controller, it can catch the maximum wind energy and operate at optimal speed ratio.

Table 1: The parameters of autonomous control PMSG wind turbine.

PMSG	Rated voltage of stator: 5 KV
	Rated frequency of stator: 50 Hz
	Rated rotor torque: 450 N·m
	Stator phase resistance: 0.01 Ω
	Armature inductance: 0.03 H
	d-axis inductance: 5.5 mH
	q-axis inductance: 3.75 mH
	Number of poles: 56
Wind turbine	Rated power: 2 MW
	Blades radius: 35 m
	Optimum tip-speed ratio: 8
	Optimum power coefficient: 0.4
	Air density: 1.225 kg/m^3
	Cut-in wind speed: 3 m/s
	Rated wind speed: 12 m/s
	Cut-out wind speed: 25 m/s
Others	Grid line voltage: 900 V
	DC-link voltage: 1200 V
	DC-link capacitor: 15000 μF
	Transformer output voltage: 12 KV
	Frequency: 50 Hz

Generators for Wind Energy Conversion

power generation normally the following Generators are used:

rrel cage Induction generators in single output mode

nd rotor Induction generators in double output mode normally known

nduction Generators (DFIG)

chronous Generators (Wound field & Permanent Magnet).

tion generators are the most commonly used generators in wind turbi

ronous generators run at fixed speed

tion generators run at variable speed (Asynchronous generators)

Induction Generator - Basic Principle of operation

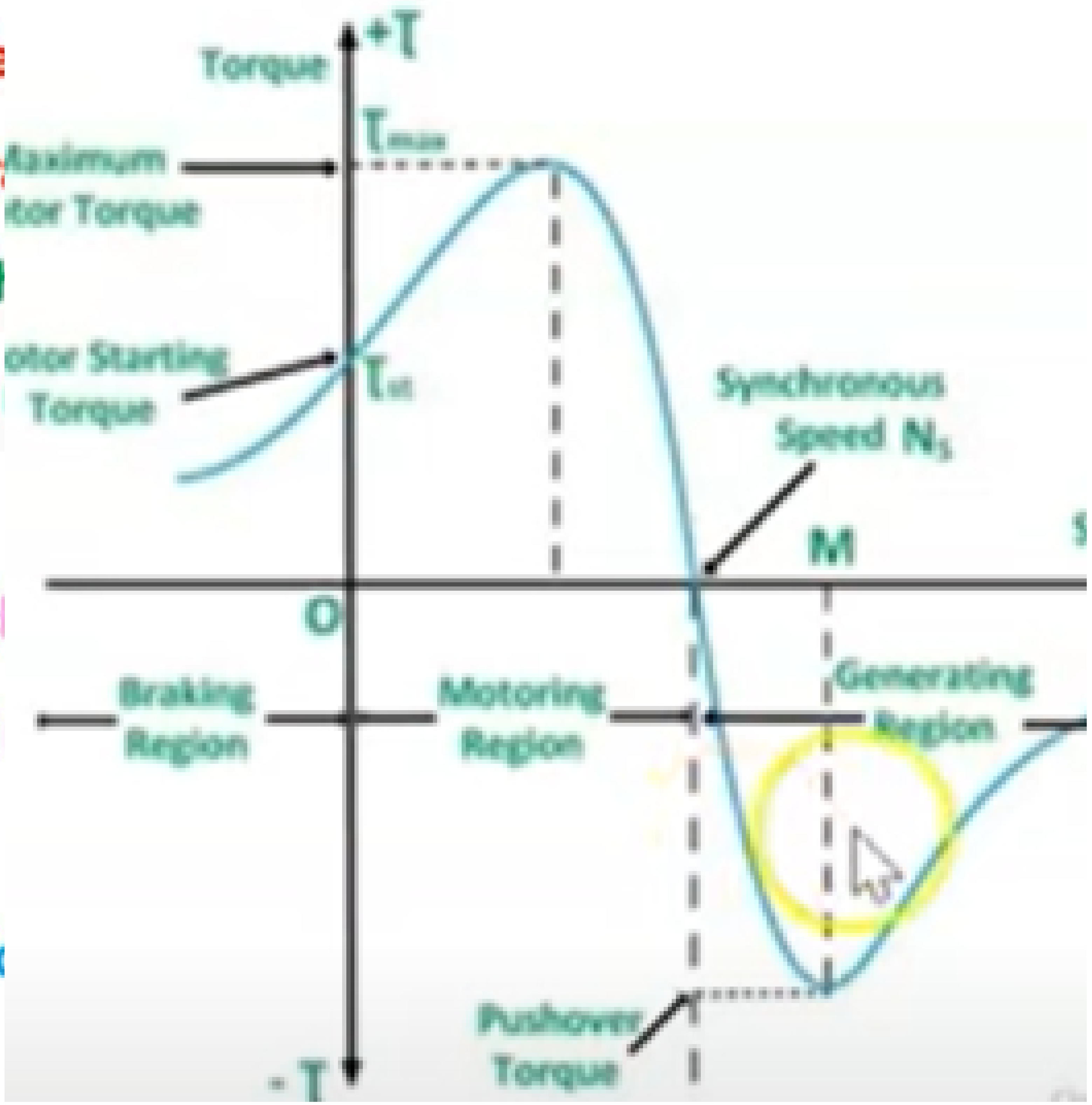
If an induction motor is driven at a speed great
synchronous speed by an external prime mover, the dire
its inducted torque will reverse and it will act as a gener

As shown in the figure (Torque-Speed Characteristics) th
maximum possible induced torque in the generator

Push over Torque

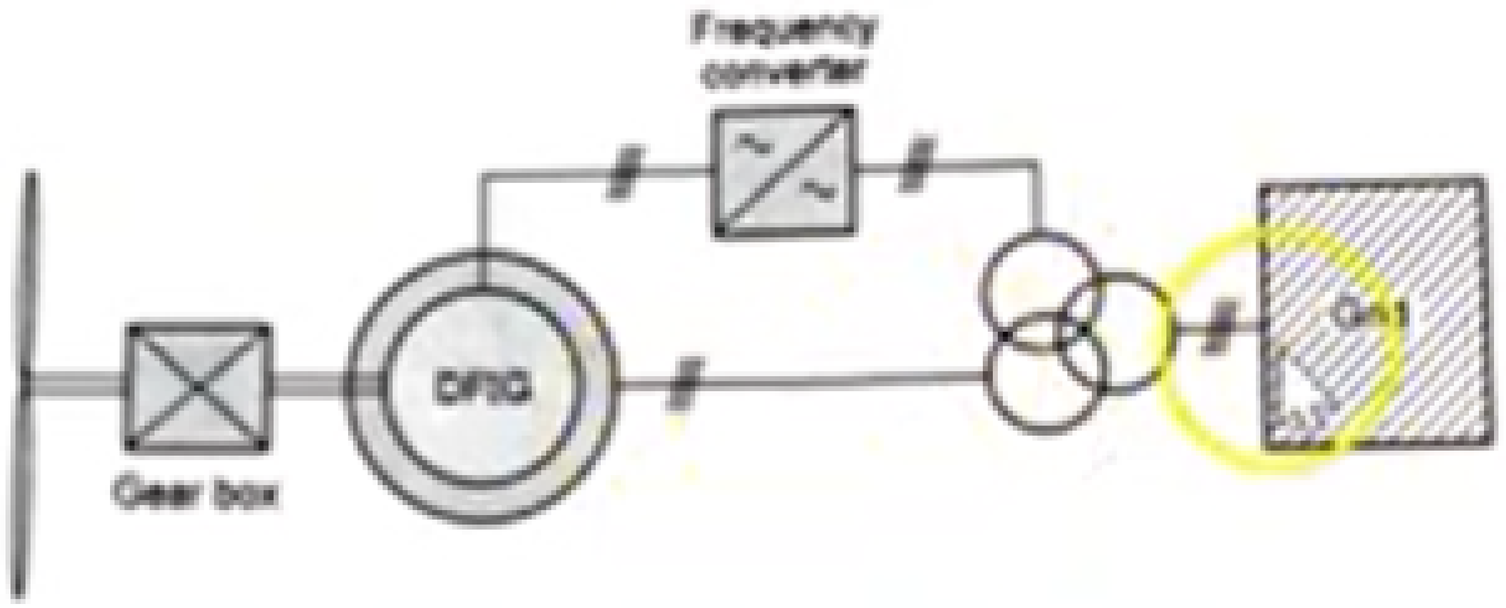
Since it lacks a separate field circuit (unlike Sync
machines) , an induction generator cannot produce
power.

An external source of reactive power must be connectec
all times to maintain its stator magnetic field

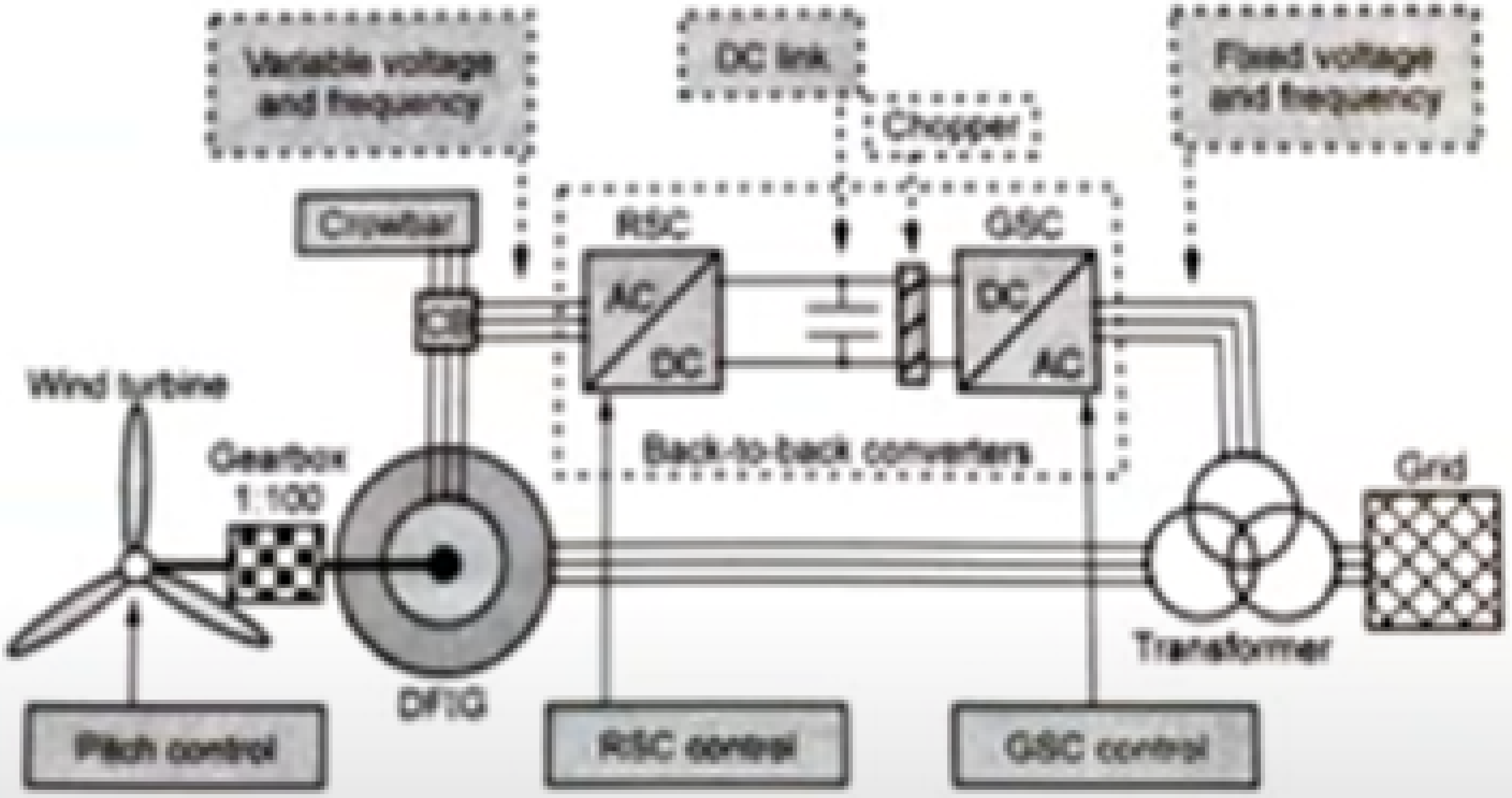


- The one great advantage of an Induction Generator is its simplicity.
- An Induction Generator does not need a separate field circuit and does not have to be driven continuously at a fixed speed unlike synchronous generator
- As long as the machine's speed is some value greater than Synchronous speed for the power system to which it is connected, it will function as a generator.

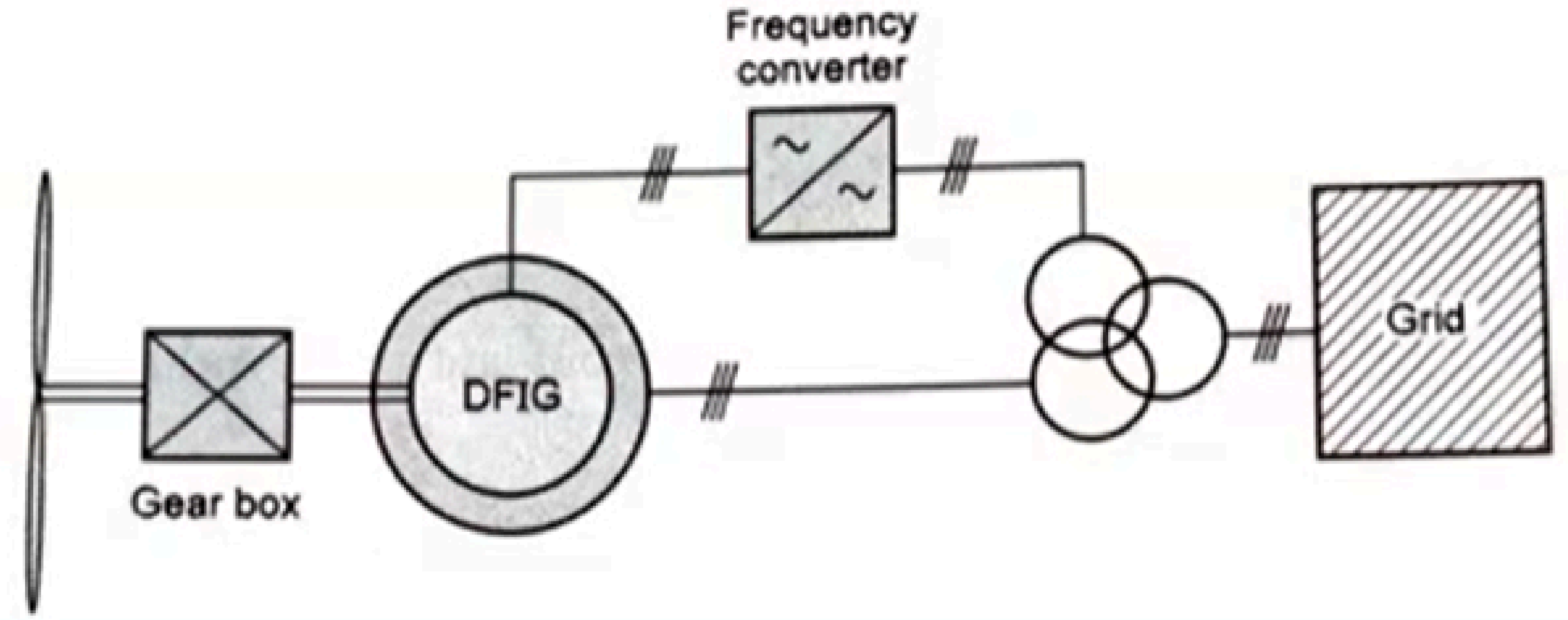
DFIG consists of Wound Rotor Induction Generator (WRIG) – stator windings are directly connected to 3 phase grid – rotor windings are connected to grid through a bidirectional back to back voltage source converter

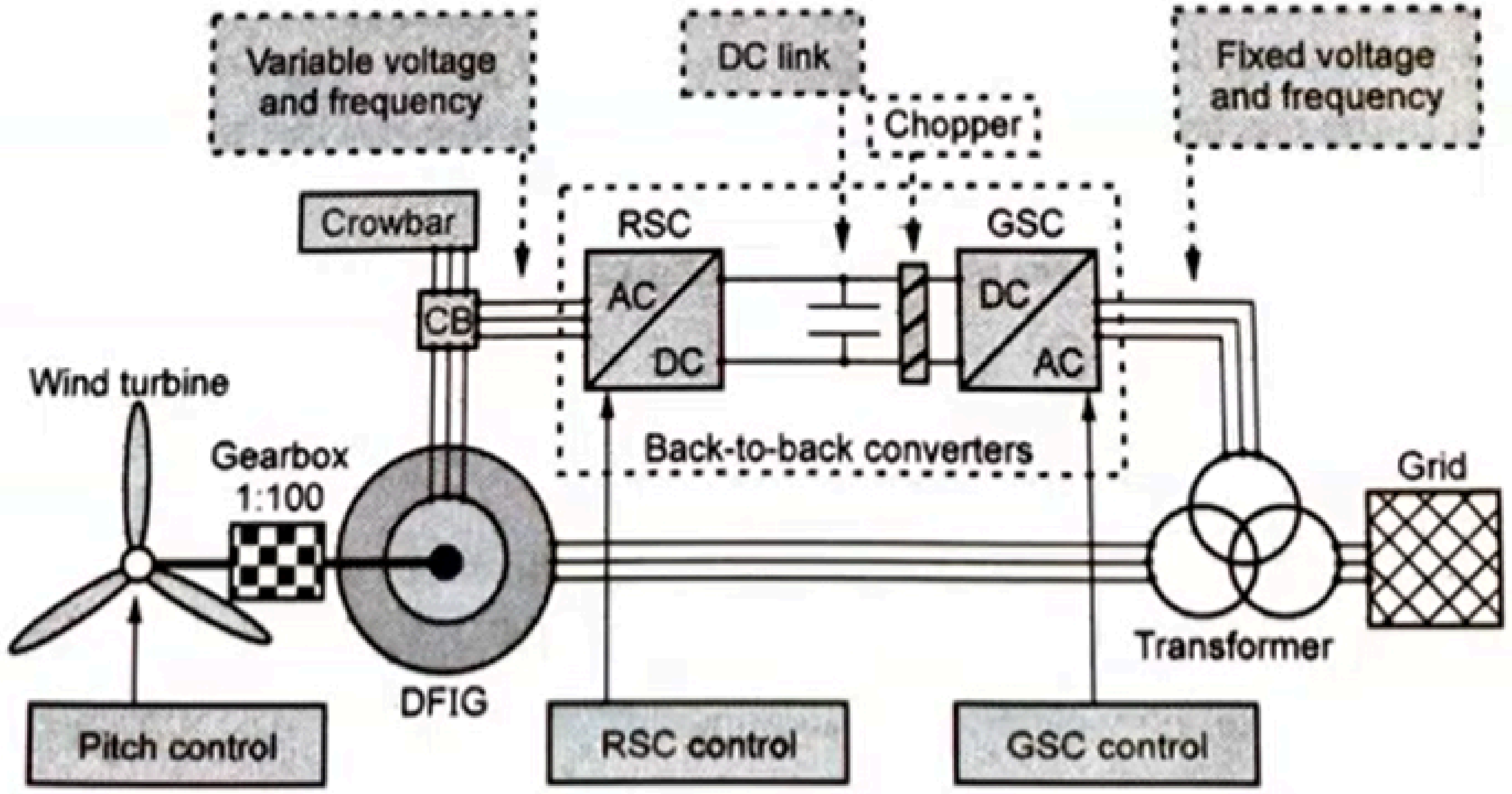


The name 'doubly fed ' is referred to the fact that voltage on stator is applied from the grid and voltage on rotor is induced by power converters

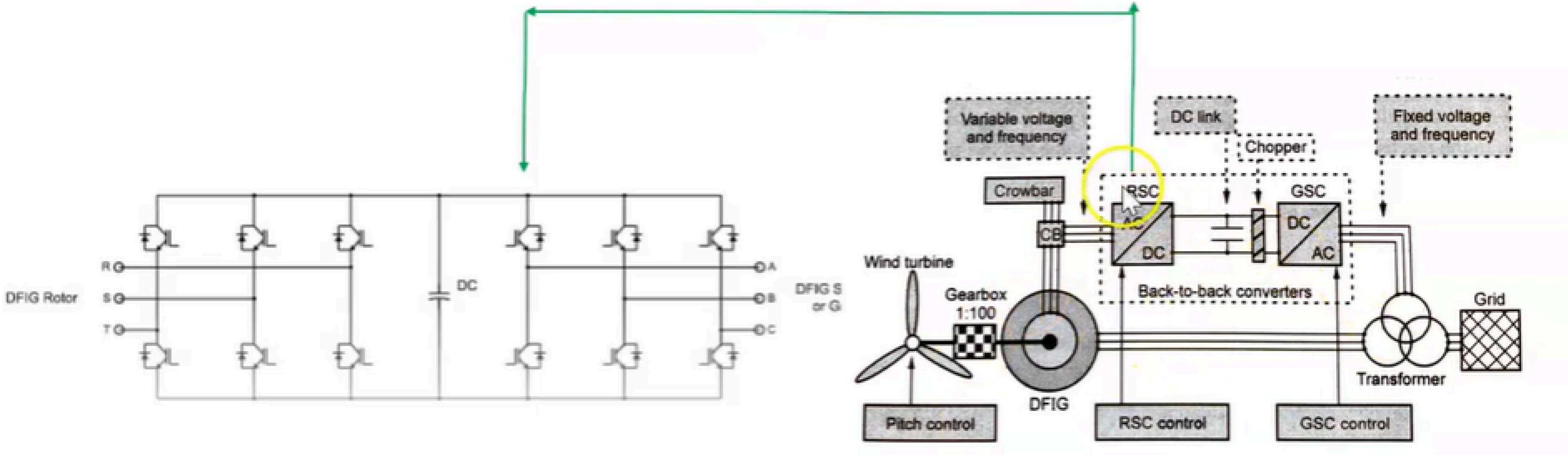


DFIG can operate at variable speeds


Frequency converter
Gear box
DFIG
Grid


Variable voltage and frequency
DC link
Chopper
Fixed voltage and frequency
Crowbar
RSC
GSC
CB
AC
DC
DC
AC
Back-to-back converters
Wind turbine
Gearbox 1:100
DFIG
Transformer
Grid
Pitch control
RSC control
GSC control

Doubly Fed Induction Generator(DFIG)-Cont.



The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected

https://www.youtube.com/watch?v=fRIHhhcL7Fk&t=821s

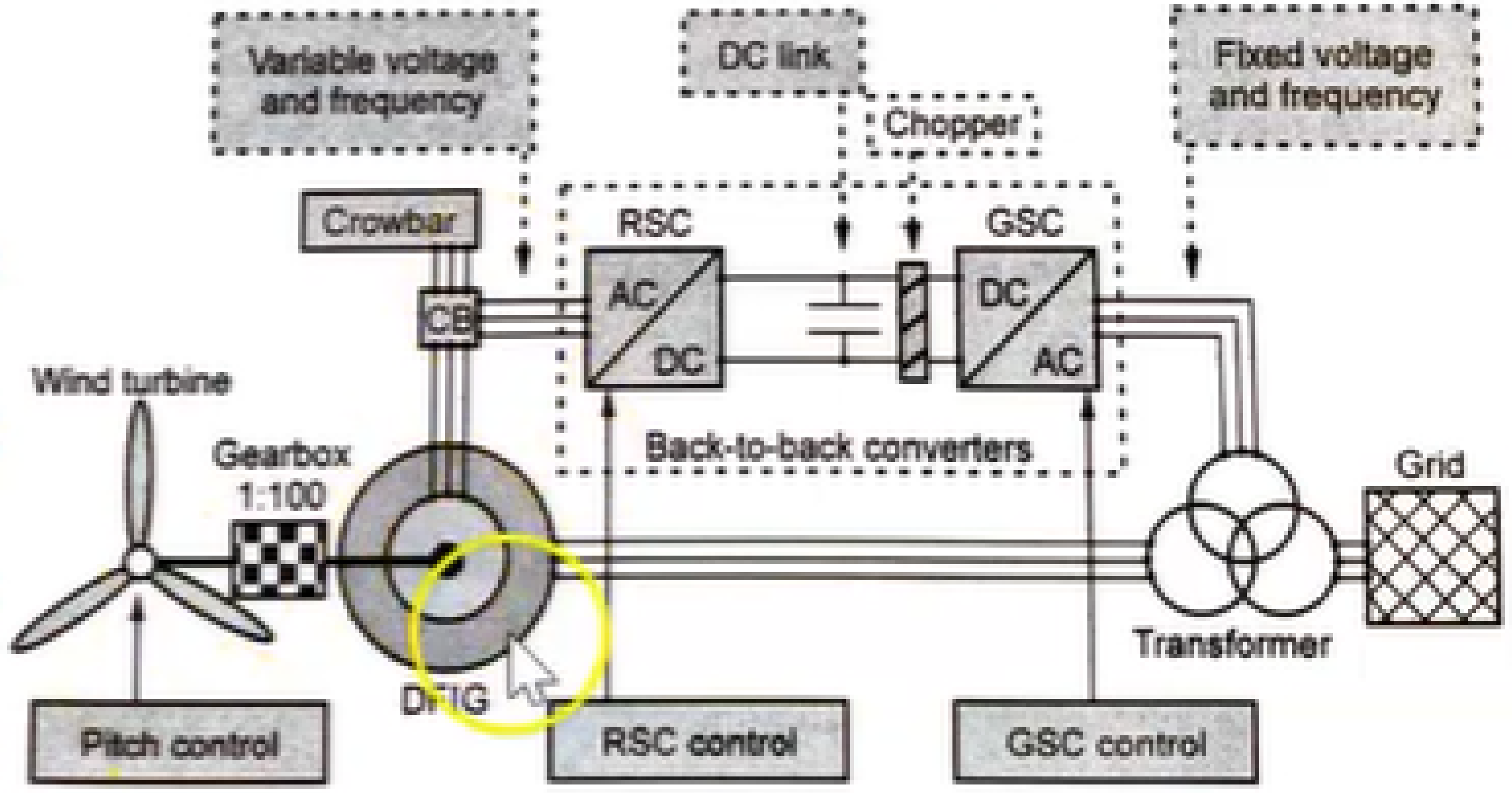
There are two power converters , one is on Grid side (GSC), And other is on Rotor side (RSC) – both can be controlled independently

The function of Rotor Side Converter is to control the generator in terms of active and reactive power by ensuring minimum power loss during power conversion- RSC converts rotor side slip frequency voltage into DC voltage or visa versa

ntrols DC link Voltage – also converts DC voltage into AC v frequency or visa versa

over-synchronous situation (rotor speed is more onous speed) power is fed from rotor to the grid and duri ronous situation (rotor speed is less than synchronous flow is from grid to rotor – using bidirectional converters

Frequency Converter



- In both condition of over –synchronous and sub-synchronous, energy is fed from stator into the grid
- Normally GSC operates at unity power factor
- The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected
- Doubly fed induction machine is a wound-rotor doubly fed electric machine and has several advantages over a conventional induction machine in wind power applications

Advantages of Doubly Fed Induction Generator (DFIG)

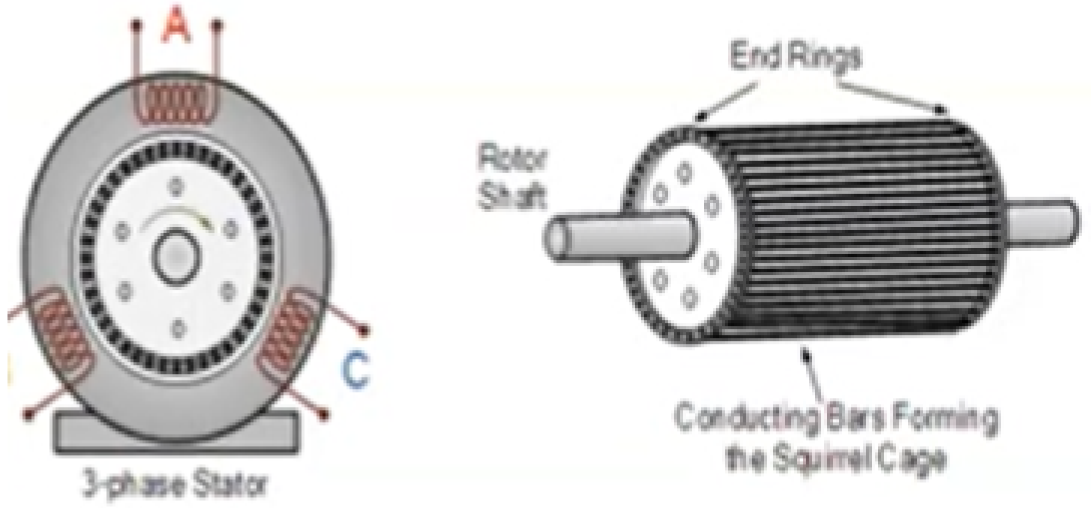
- The primary advantage of Doubly-Fed Induction Generators (DFIG) when used in wind turbines is that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor.
- DFIG is able to control Reactive Power and thus power factor can be improved (using Converters)
- It is also possible to decouple active and reactive power control by independent control of rotor excitation current

Limitation – Need of Slip ring, Converter cost etc

- it is very sensitive to grid faults.

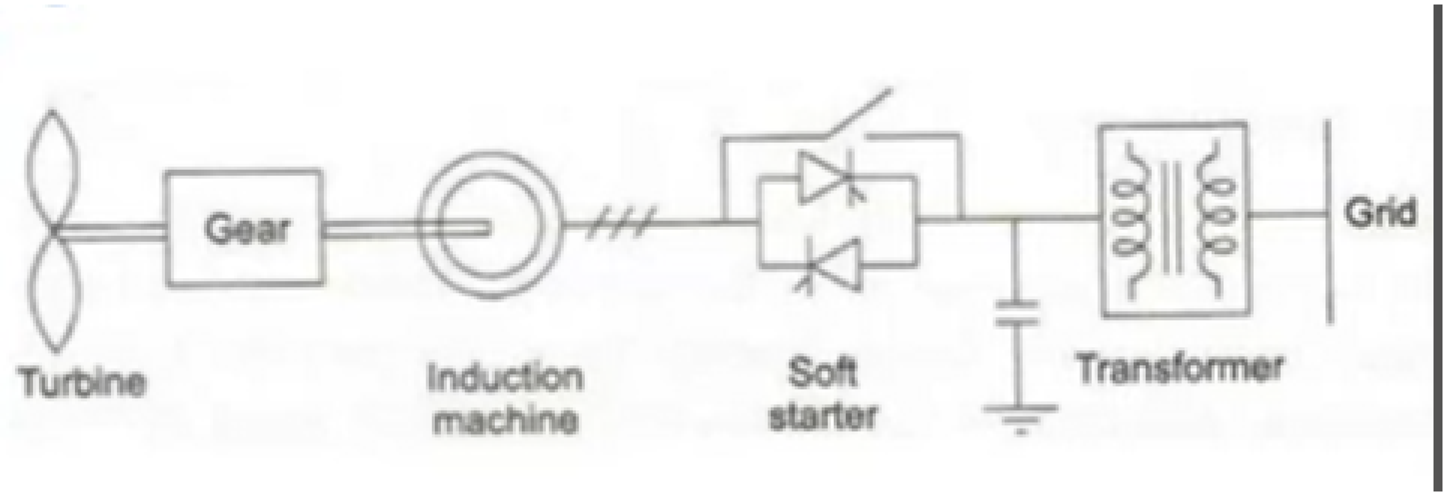
Squirrel Cage Induction

- Rotor is made up of a cylindrical core with copper /Aluminium bars Short circuited at both ends by End rings
- Stator contains windings that are connected to grid
- SCIG operates based on electromagnetic induction where rotor is not directly excited but induced from magnetic field by stator
- As wind rotates the turbine blades, the mechanical energy is transferred to SCIG's rotor causing to rotate
- This rotation induces a current in the rotor bars



Squirrel Cage Induction Generators- Grid connected mode

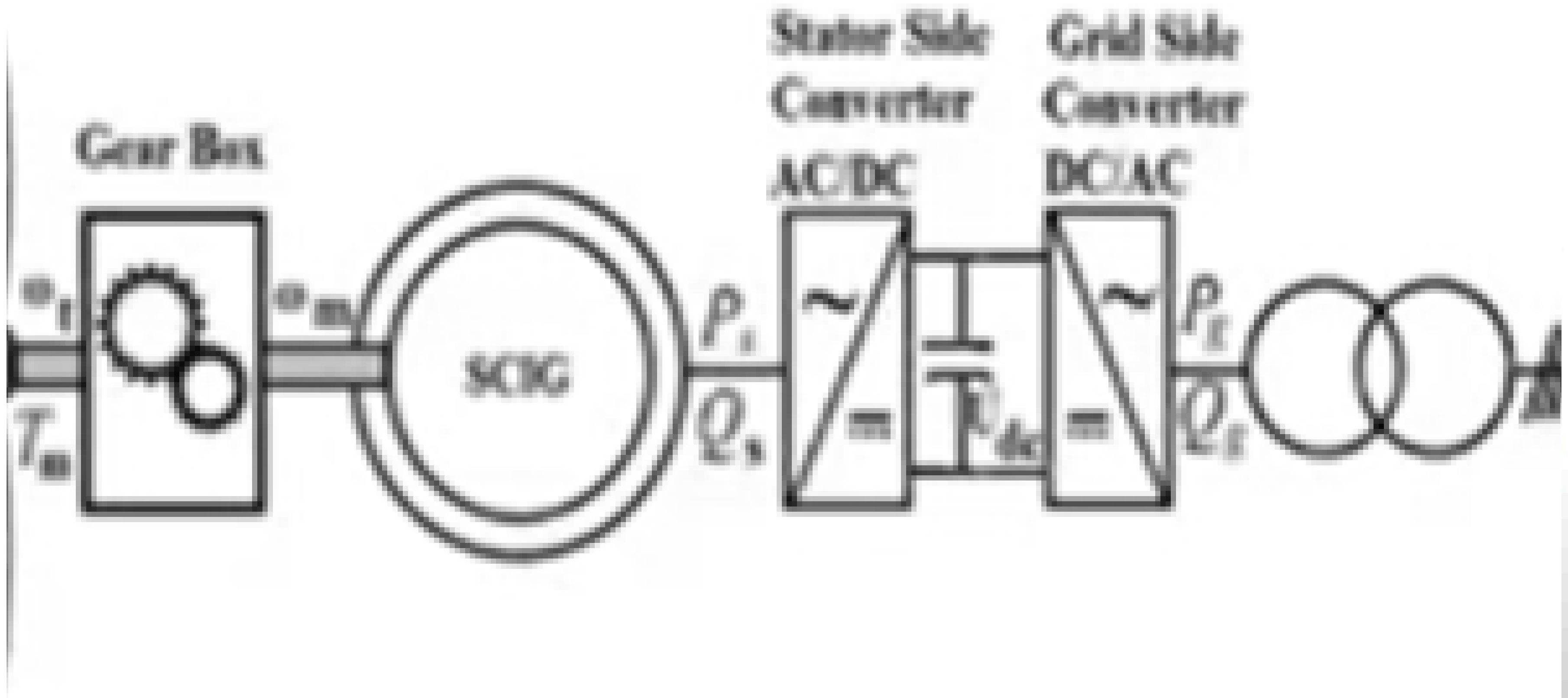
Fixed Speed Wind Turbine system with a Squirrel Cage Induction Generator coupled to a turbine through a gear box. The gear box steps up the rotor speed to a value matching a 50 or 60 Hz utility network. (1500 or1800 RPM for a 4 pole machine)



Nacelle, Gear box can be used to convert the rotor speed to the required speed so that the Generator output can be connected to the Grid directly

- Soft starter is a solid-state device that protects AC electric motors from damage caused by sudden influxes of power by limiting the large initial inrush of current associated with motor startup.

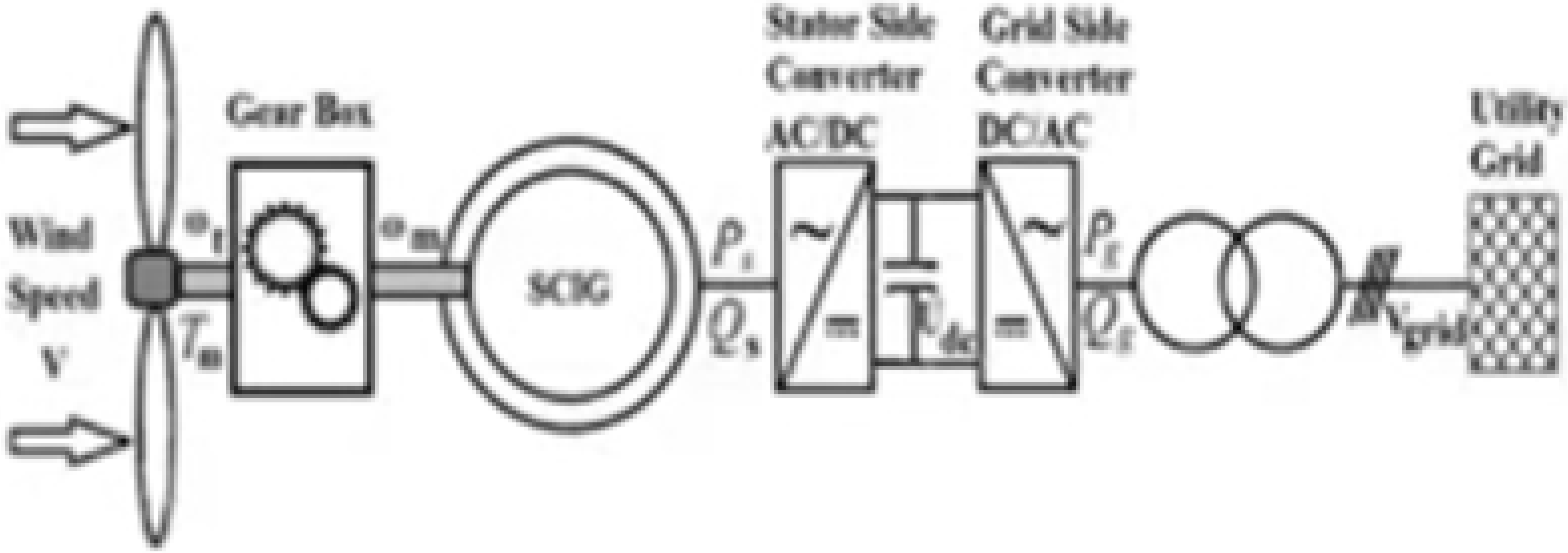
Squirrel Cage Induction Generator(SCIG)



In WECS, SCIGs are used in conjunction with gear box to match the turbine's mechanical speed to generators required operating speed

The gear box steps up the slow rotation of turbine to higher speeds required by SCIG

Generator output at any frequency and voltage can be converted to Grid compatible voltage and frequency using Power Electronic converters and Inverters


Wind
Speed
V
Gear Box
SCIG
Stator Side
Converter
AC/DC
Grid Side
Converter
DC/AC
Utility
Grid

Advantages of Squirrel Cage Induction Generator (SCIG) used in Wind Power Plant

1. Better wind energy utilization.
2. Reduces reactive power demand on self-excited capacitor bank.
3. Very simple in construction, robust size, rugged construction.
4. Cost is less.
5. Rectifier can generate excitation current for generator.
6. Fast transient response.
7. Few parts, so reliable operation.

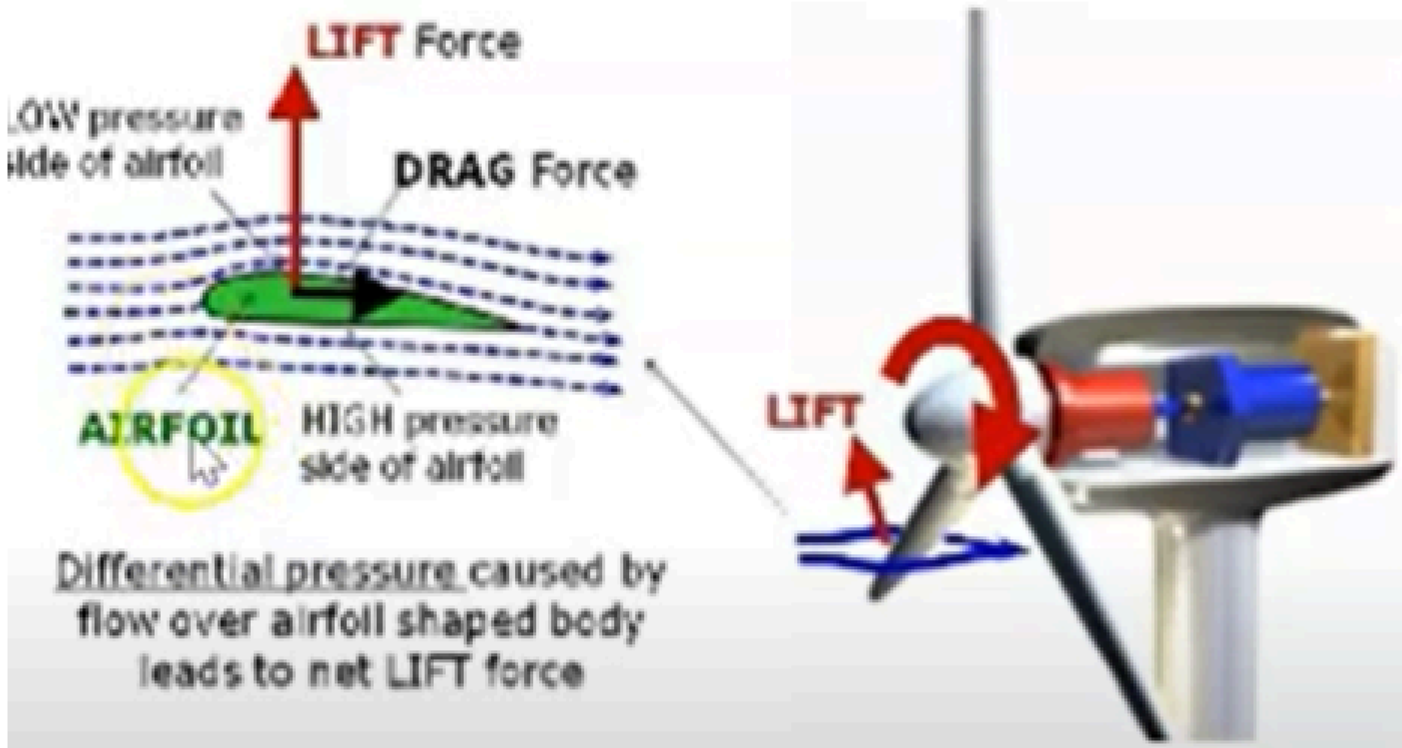
Disadvantages of Squirrel Cage Induction Generator(SCIG) used in Wind Power Plant

1. Noisy operation.
2. It has very low efficiency.
3. Additional components such as reactive power compensator is required in the circuit.
4. For smooth grid connection, a soft starter is required.
5. Gear box maintenance is frequent, so cost increases.

Wind Turbine Controls

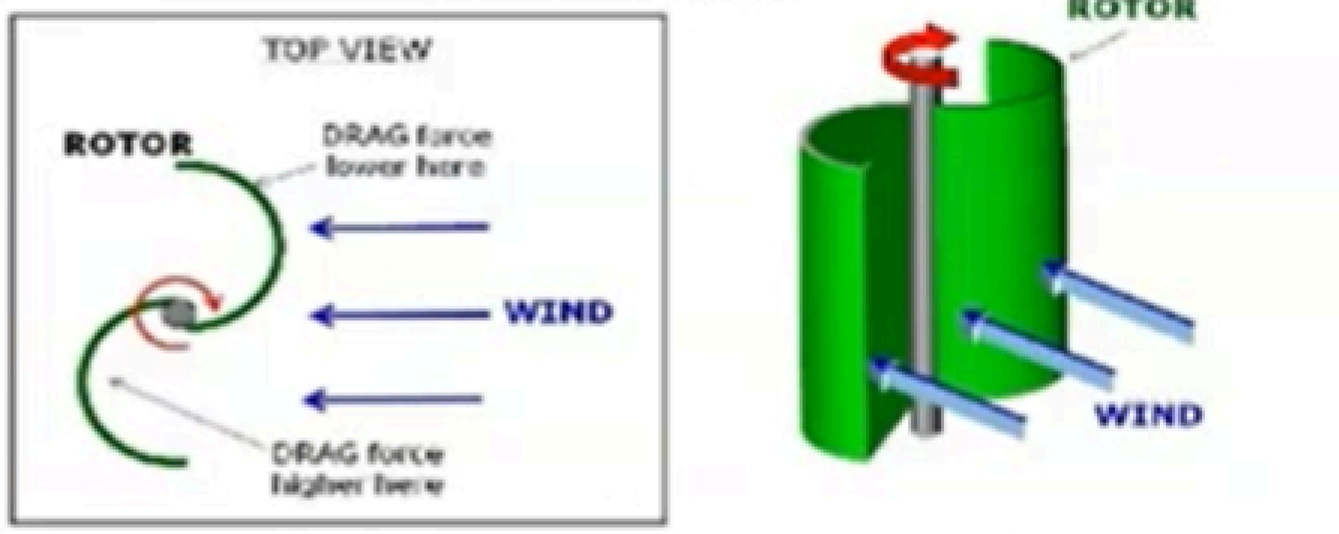
Wind Turbine Concept- Lift Based & Drag Based

Lift-based Wind Turbine Concept



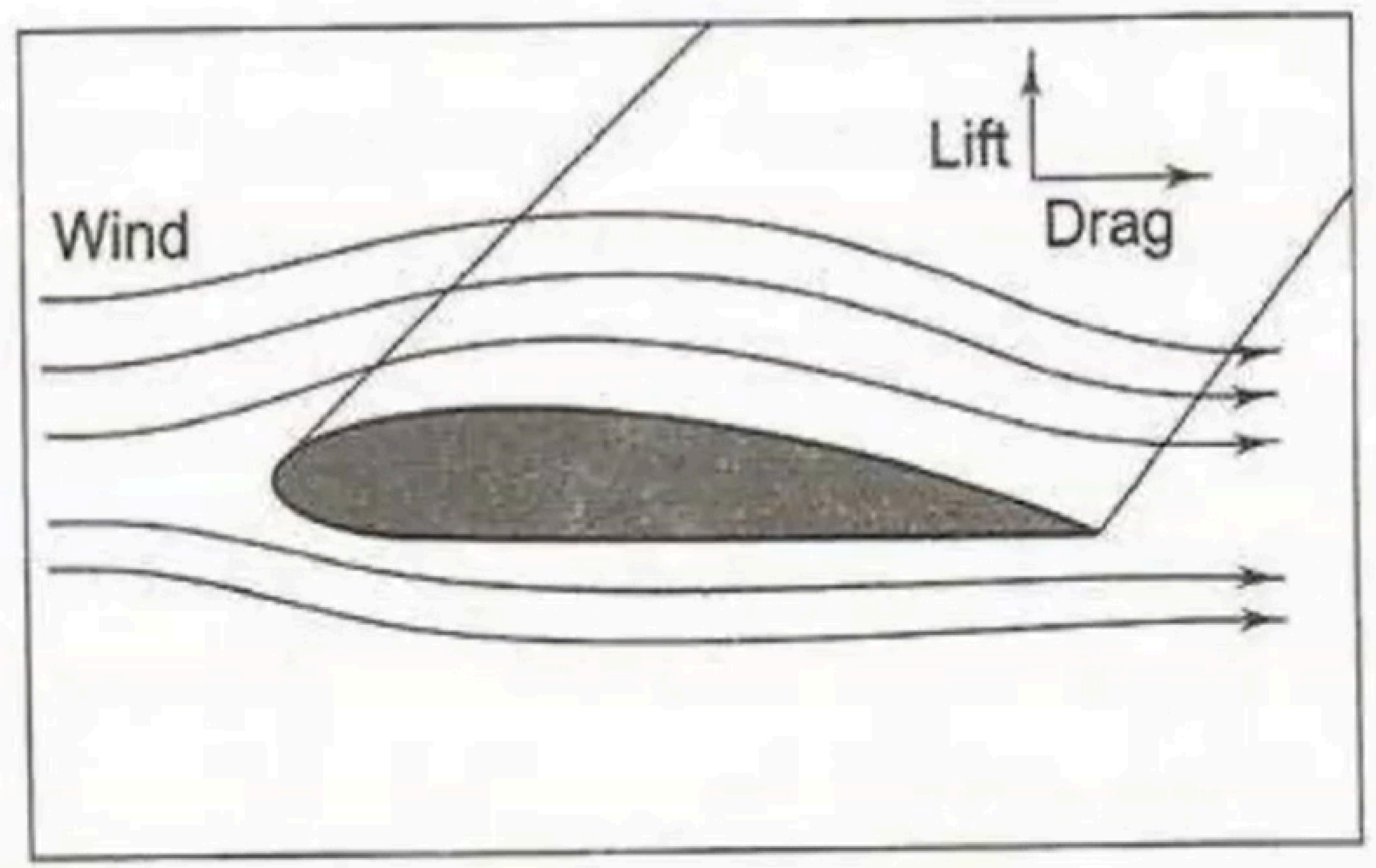
Differential pressure caused by flow over airfoil shaped body leads to net LIFT force

Drag-based Wind Turbine Concept
(Savonius Rotor)



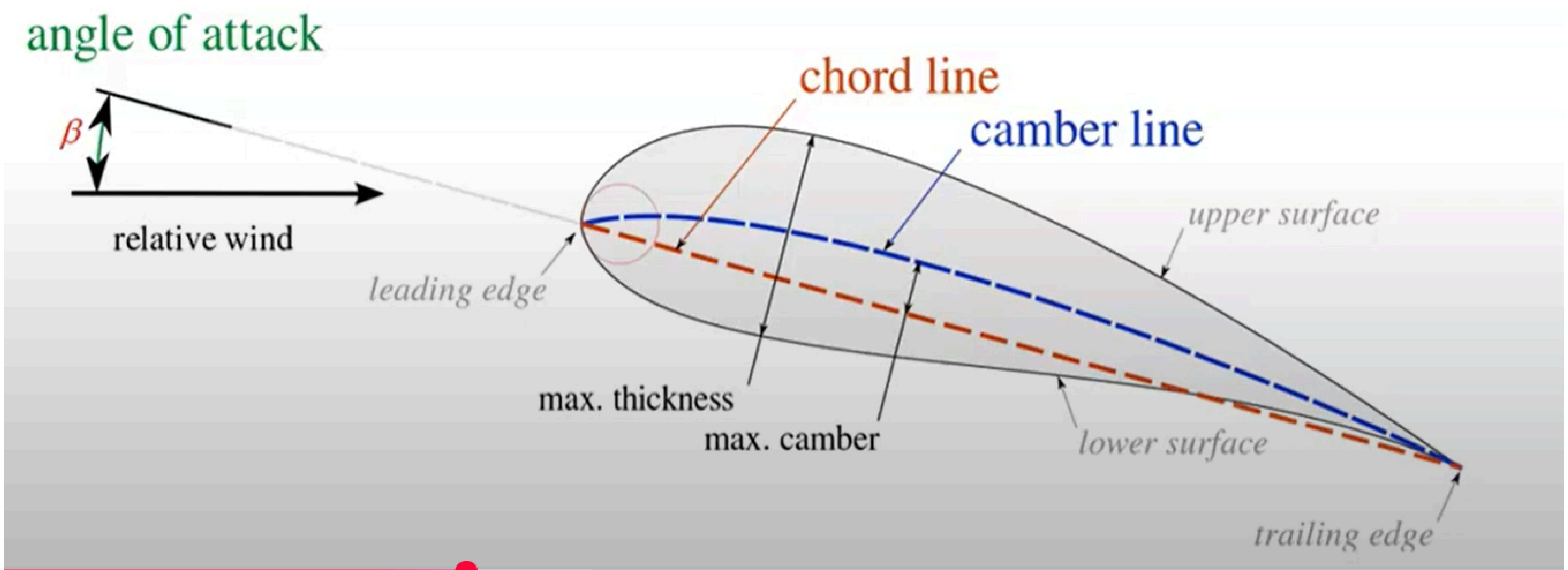
Rotation created by difference in DRAG forces on the convex and concave surfaces of the rotor

- *The wind stream at the top of the aerofoil has to traverse a longer path than that at the bottom, leading to a difference in velocities. This gives rise to a difference in pressure (Bernoulli's principle) from which 'lift force' results*
- There is another force that tries to push the aerofoil in the direction of the wind. This is called the 'drag force'. The net force on the aerofoil is then determined by the resultant of these two forces

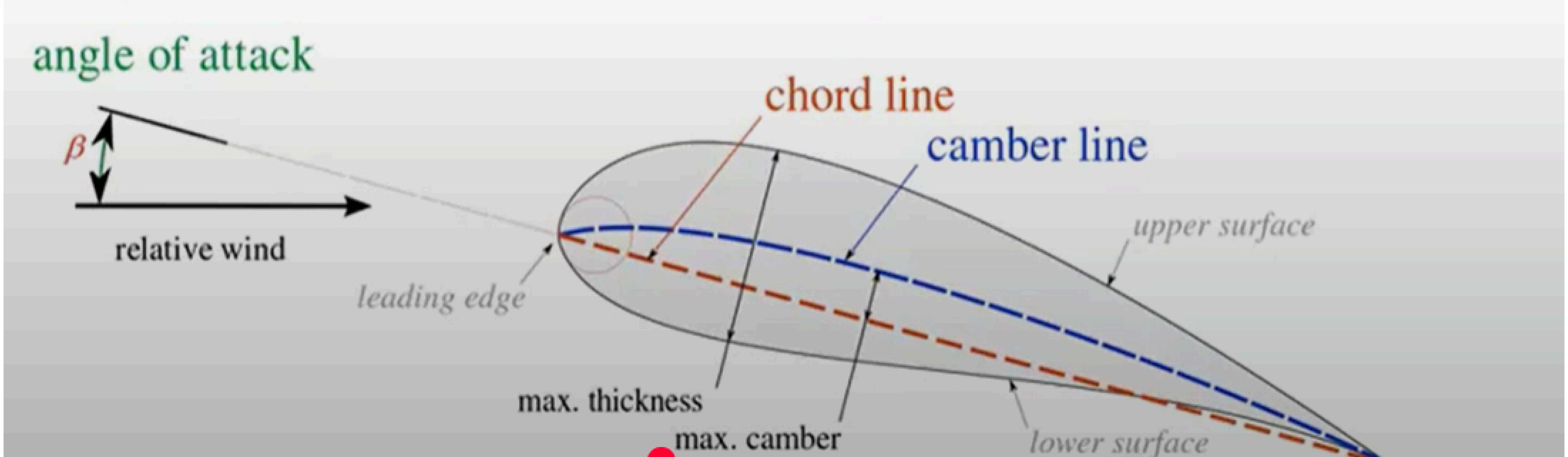


Nomenclature of Aerofoil and basic definitions

- ***Leading edge:*** This is the point at the front of the aerofoil that has maximum curvature.
- ***Trailing Edge:*** This is defined similarly as the point of maximum curvature at the rear of the aerofoil.
- ***Chord Line:*** This is a straight line connecting the leading and trailing edges of the aerofoil.

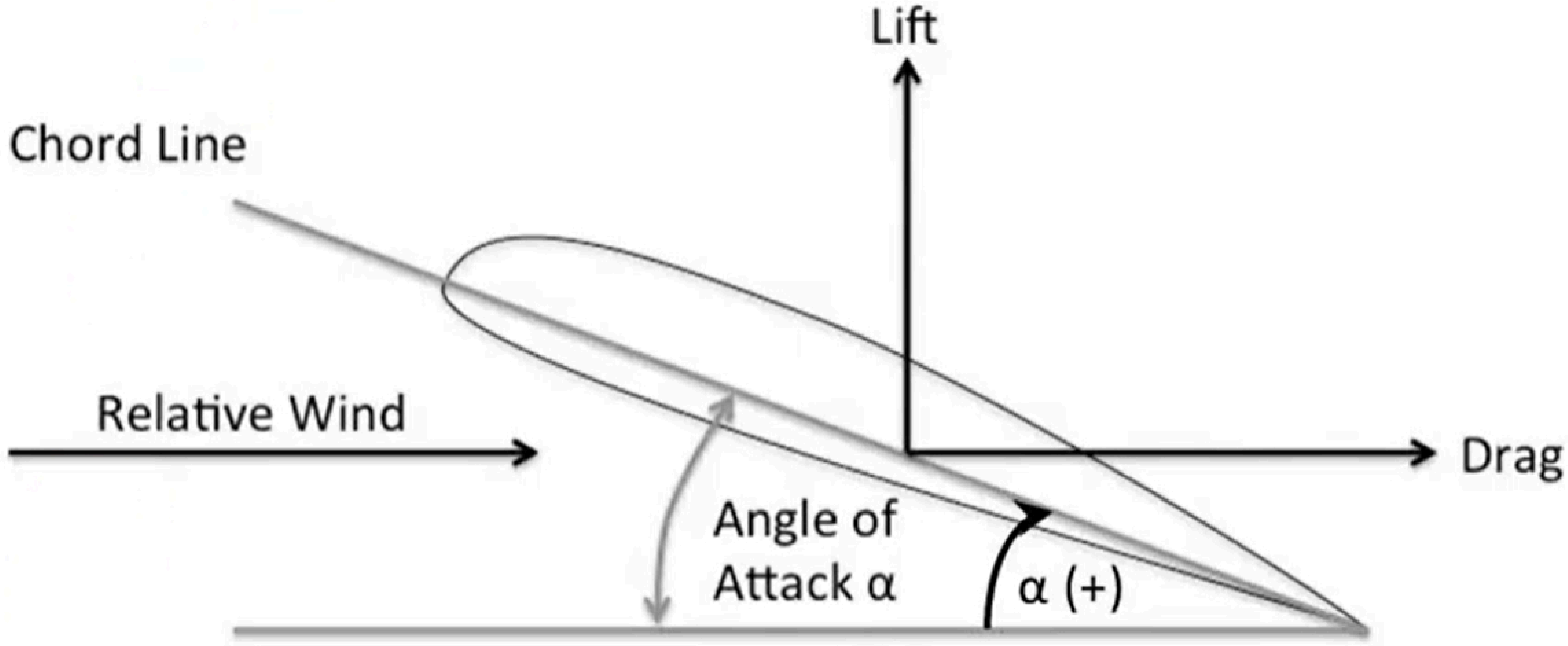


- *Chord Length:* Chord Length, is the length of the chord line and is the characteristic dimension of the aerofoil section.
- *Pitch angle (β): The angle between the chord of the aerofoil section and the plane of rotation, also called as setting angle.*
- *Angle of Inclination (I):* The angle between the relative velocity vector and the plane of rotation is called as angle of inclination
- Solidity: Ratio of blade area to swept area



- ***Lift force:*** **It is the component of aerodynamic force in the direction perpendicular to the relative wind**

- ***Drag force:*** **It is the component of aerodynamic force in the direction of relative wind**



- **Tip Speed Ratio (TSR): Ratio of the speed of the outer blade tip divided to the undisturbed natural speed of the wind**

- **Start-up speed: Wind speed at which the wind turbine blades will begin to rotate**

- **Cut-in speed: Wind speed required for a particular wind turbine to begin to generate electric power**

- **Cut-out speed: This is the speed at which the turbine blades are brought to rest to avoid damage from high winds**

$$\text{Tip Speed Ratio, TSR, } \lambda = \frac{\text{Tip speed of blade}}{\text{Wind speed}}$$

$$\lambda = \frac{\omega R}{v}$$

R=Radius of rotor in meters

v=speed of wind in meters/sec

Rotor efficiency versus tip speed ratio

- **Rotor efficiency versus Tip Speed Ratio (TSR) for rotors with different number of blades. Two-blade rotors have the highest efficiency**