Project proposal of e- Content for Post Graduate courses

Wind Energy Conversion System

Principal Investigator

B. Hemalatha M.E., MBA

Assistant Professor, Electrical and Electronics Engineering

LATHAMATHAVAN ENGINEERING COLLEGE
ALAGAR KOIL, MADURAI – 625 301, TAMILNADU.
LATHA MATHAVAN ENGINEERING COLLEGE

Latha Mathavan Engineering College was established on 23rd September 2007 run by Karuppiyah Pillai Theivanaiammal Educational Trust and it was approved by AICTE, New Delhi and affiliated to Anna University, Chennai. 750 students are studying in our college. The college functions with 120 Teaching staff and 50 Non-Teaching Staff. Our college has received ISO 9001: 2008 certification from TUV SUD, Germany. Besides the college signed MOU with several companies. The college installed a 50 KW solar wind hybrid power Generation at the cost of 1Crore. We have secured the department of Civil Engineering, Computer Science and Engineering, Electronics and Communication Engineering, Mechanical Engineering and Science and Humanities. Training and Placement cell holds a remarkable placement profile for every year. Our institution facilitated with various ONCAMPUS & OFF-CAMPUS PLACEMENT. Our institution started women empowerment cell on 8th March 2012. The main objective of this cell is to empower girl students by sharing the issues – professional and personal front and finding Solutions. The College provides good and safe hostel facilities for both boys and girls to cater to the needs of outstation students. Two Generator facilities are also available in our college. In addition, the college has implanted Mineral water facility at 3 locations in our college premises. The activities of the NSS and NCC unit of our college are for the benefit of the society at large.
**Biography:** Mrs. B. Hemalatha

Mrs. B. Hemalatha is an Assistant Professor in the department of Electrical and Electronics Engineering, Latha Mathavan Engineering College, Madurai. She received the degrees B.E. (EEE) from P.S.N.A. College of Engineering and Technology, Dindigul and M.E. (Power Management) from Anna University, Regional centre, Madurai and MBA (Finance) in Alagappa University.

She has presented 3 papers in national and international conferences. She has 4 years of teaching experience. She has handled various papers in the field of Electrical and Electronics engineering in her teaching career.
WIND ENERGY CONVERSION SYSTEM

ABSTRACT

The prime objective of choosing “wind energy conversion system” is to know the utilization of upper and lower wind turbines assemblies which are rotated in opposite directions about a vertical rotation axis. An additional object of the present invention is to understand the blade adjustment pitch for counter-rotating blade assemblies which has to control the rotational speed of the blade assemblies, to establish nominal conversion of wind velocity into torque, stator to control output voltage and to regulate maximum power and/or shear forces in a wind energy conversion system.

In industrial areas, WECS is done by using a constant speed direct-driven wind turbine in MATLAB. Moreover, by maintaining the dc link voltage at its reference value, the output ac voltage of the inverter can be kept constant irrespective of variations in the wind speed and load. An effective control technique to extract maximum power from wind turbine is maximum power point tracking controller (MPPT), grid side controller also called voltage controller, pitch controller, phase lock loop controller (PLL) also used transformer used for isolation purpose, crow bar circuit used for protection the whole system.
UNIT I INTRODUCTION

Components of WECS-WECS schemes-Power obtained from wind-simple momentum theory-Power coefficient-Sabinin’s theory-Aerodynamics ofWind turbine

UNIT II WIND TURBINES

HAWT-VAWT-Power developed-Thrust-Efficiency-Rotor selection-Rotor design considerations- Tip speed ratio-No. of Blades-Blade profile-Power Regulation-yaw control-Pitch angle controlstall control- Schemes for maximum power extraction.

UNIT III FIXED SPEED SYSTEMS

Generating Systems- Constant speed constant frequency systems -Choice of Generators- Deciding factors-Synchronous Generator-Squirrel Cage Induction Generator- Model of Wind Speed- Model wind turbine rotor - Drive Train model- Generator model for Steady state and Transient stability analysis.

UNIT IV VARIABLE SPEED SYSTEMS

Need of variable speed systems-Power-wind speed characteristics-Variable speed constant frequency systems synchronous generator- DFIG- PMSG -Variable speed generators modelling - Variable speed variable frequency schemes.

UNIT V GRID CONNECTED SYSTEMS

Wind interconnection requirements, low-voltage ride through (LVRT), ramp rate limitations, and supply of ancillary services for frequency and voltage control, current practices and industry trends wind interconnection impact on steady-state and dynamic performance of the power system including modelling issue.

TOTAL: 45 PERIODS

TEXT BOOKS


REFERENCES

4. N. Jenkins,“Wind Energy Technology” JohnWiley & Sons,1997

SYLLABUS COPY LINK:
https://www.annauniv.edu/academic_courses/WSA/03.%20Electrical/03.%20Pow%20sys%20E.pdf
# COURSE DELIVERY PLAN

**Subject Name**: Wind Energy Conversion System  
**Name Of Faculty**: Mrs.B. Hemalatha

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Actuator Disc Concept, Power Obtained from Wind, Density of Air  
Rotor Area, Wind Velocity  
Energy Conversion In Wind, Momentum Theory, Bernoulli for Rotating Wake  
Pre-Rotor, Post-Rotor  
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| **UNIT-II** | HAWT & VAWT, Power Developed, Thrust, Efficiency  
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Choice of the Pitch Angle, Tip Speed Ratio, Power Speed Characteristics, Torque Speed Characteristics, Solidity, No. of Blades, Blade Profile  
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Asynchronous Generator, Wound Rotor Induction Generator (WRIG)  
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Synchronous Generating, Asynchronous Generator, Squirrel Cage Induction Generator - Model of Wind Speed  
Model Wind Turbine Rotor, Drive Train Model, Generator Model for Steady State and Transient Stability Analysis  
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Transient, Short Circuit Contributions |
| **UNIT-IV** | Need of Variable Speed Systems, Power Wind Speed Characteristics- Cut-In Speed, Cut-Out Speed, Rated Output Power and Rate Output Wind Speed, Wind Turbine Efficiency or Power Coefficient  
The Betz Limit on Wind Turbine Efficiency, Variable Speed Constant Frequency Systems, Synchronous Generators, Synchronous Generator and Diode-Thyristor Converter, Doubly-Fed Induction Generators (DFIG), Squirrel-Cage Induction Generators (SCIG) |
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**CASE STUDY**

- Wind pumps for irrigation

**REFERENCES:**

1. Wind Energy Systems by Dr. Gary L. Johnson
3. Tony Burton, David Sharpe, Nick Jenkins Ervin Bossanyi, Garrad Hassan & Partners, wind energy Handbook

**WEBSITE REFERENCES:**

2. [http://www.windenergy.nref.in](http://www.windenergy.nref.in)
3. [https://teachergeek.org/wind_turbine_types.pdf](https://teachergeek.org/wind_turbine_types.pdf)
UNIT –I - INTRODUCTION

The wind energy conversion system (WECS) includes wind turbines, generators, control system, interconnection apparatus. Wind Turbines are mainly classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Modern wind turbines use HAWT with two or three blades and operate either downwind or upwind configuration. This HAWT can be designed for a constant speed application or for the variable speed operation. Among these two types variable speed wind turbine has high efficiency with reduced mechanical stress and less noise. Variable speed turbines produce more power than constant speed type, comparatively, but it needs sophisticated power converters, control equipments to provide fixed frequency and constant power factor.

1.1 COMPONENTS OF WECS

Early wind machines ranged in their rated powers from 50 to 100 kW, with rotor diameters from 15 to 20 meters. Commercial wind turbines now have ratings over 1 MW and machines for the land based and offshore applications have rated power outputs reaching 5 and even 7-10 MW of rated power for off-shore wind applications.

![Schematic of wind turbine components.](image)

Larger sizes are mandated by two reasons. They are cheaper and they deliver more energy. Their energy yield is improved partly because the rotor is located higher from the ground and so intercepts higher velocity winds, and partly because they are more efficient. The productivity of the 600 kW machines is around 50 percent higher than that of the 55 kW machines. Reliability has improved steadily with wind turbine manufacturers guaranteeing availabilities of 95 percent.

1.1.1 Wind energy systems include the following major components

The rotor and its blades, the hub assembly, the main shaft, the gear box system, main frame, transmission, yaw mechanism, overspeed protection, electric generator, nacelle, yaw drive, power conditioning equipment, and tower (Fig.1.1).

1.2 WIND TURBINE AERODYNAMICS
The wind turbine rotor interacts with the wind stream, resulting in a behaviour named aerodynamics, which greatly depends on the blade profile.

### 1.2.1 Actuator Disc Concept

The analysis of the aerodynamic behaviour of a wind turbine can be done, in a generic manner, by considering the extraction process (Burton et al. 2001).

Consider an actuator disc (Figure 1.2) and an air mass passing across, creating a stream-tube.

![Diagram of actuator disc](image)

**Figure 1.2. Energy extracting actuator disc**

The conditions (velocity and pressure) in front of the actuator disc are denoted with subscript $u$, the ones at the disc are denoted with 0 and, finally, the conditions behind the disc are denoted with $w$. The momentum $H m (v_u - v_w)$ transmitted to the disc by the air mass $m$ passing through the disc with cross-section $A$ produces a force, expressed as

$$T = \frac{\Delta H}{\Delta t} = \frac{\Delta m (v_u - v_w)}{\Delta t} = \rho A v_0 (v_u - v_w)$$

Using Bernoulli’s equation, the pressure difference is

$$P_0^+ - P_0^- = \frac{1}{2} \rho (v_u^2 - v_w^2)$$

and, replacing Equations results in

$$T = \frac{1}{2} \rho A (v_u^2 - v_w^2)$$

From Equations the kinetic energy of an air mass travelling with a speed $v$ is

$$E_k = \frac{1}{2} m v^2$$

where $m$ is the air mass that passes the disc in a unit length of time, e.g., $m = \rho A v_0$, then the power extracted by the disc is

$$P = \frac{1}{2} \rho A v_0 (v_u^2 - v_w^2)$$

The *power coefficient*, denoting the power extraction efficiency, is defined as

$$P = \frac{1}{2} \rho A v^3 a (1-a)^2.$$
The maximum value of $C_p$ occurs for $a = 1.3$ and is $C_{p_{\text{max}}} = 0.59$, known as the Betz limit (Betz 1926) and represents the maximum power extraction efficiency of a wind turbine.

1.3 POWER OBTAINED FROM WIND

A wind turbine obtains its power input by converting the force of the wind into torque (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

1.3.1 Density of air. The kinetic energy of a moving body is proportional to its mass. The kinetic energy in the wind thus depends on the density of the air, i.e. its mass per unit of volume. In other words, the “heavier” the air, the more energy is received by the turbine. At normal atmospheric pressure and at 15°C, the density of air is 1.225 kg/m$^3$, which increases to 1.293 kg/m$^3$ at 0°C and decreases to 1.164 kg/m$^3$ at 30°C. In addition to its dependence upon temperature, the density decreases slightly with increasing humidity. At high altitudes (in mountains), the air pressure is lower, and the air is less dense. It will be shown later in this chapter that energy proportionally changes with a variation in density of air.

1.3.2 Rotor area. When a farmer tells how much land he is farming, he will usually state an area in terms of square meters or hectares or acres. With a wind turbine it is much the same story, though wind farming is done in a vertical area instead of a horizontal one. The area of the disc covered by the rotor (and wind speeds, of course), determines how much energy can be harvested over a year. A typical 1,000 kW wind turbine has a rotor diameter of 54 m, i.e. a rotor area of some 2,300 m$^2$. The rotor area determines how much energy a wind turbine is able to harvest from the wind. Since the rotor area increases with the square of the rotor diameter, a turbine which is twice as large will receive $2^2$, i.e. four times as much energy.

1.3.3 Wind velocity. Considering an area $A$ (e.g. swept area of blades) and applying a wind velocity $v$, the change in volume with respect to the length “l” is:

$$V = A \cdot l,$$

$$V = l/t.$$

The energy in the wind is in the form of kinetic energy. Kinetic energy is characterized by the equation:

$$E = 1/2mv^2$$

The change in energy is proportional to the change in mass, where
\[ m = V \cdot \rho a \]

and \( \rho a \) the specific density of the air. Therefore, substituting for \( V \) and \( m \) yields

\[ E = \frac{1}{2} A \cdot \rho a \cdot v^3 \cdot t \]

1.3.4 Energy Conversion in Wind

Fig. 1.4 Relationship between wind velocity and power of wind (wind speed for Germany)

From the previous equation it can be seen that the energy in the wind is proportional to the cube of the wind speed, \( v^3 \). The power \( P \) is defined as

Therefore, power in wind is proportional to \( v^3 \). From Fig. 3 it can be seen that the power output per m\(^2\) of the rotor blade is not linearly proportional to the wind velocity, as proven in the theory above. This means that it is more profitable to place a wind energy converter in a location with occasional high winds than in a location where there is a constant low wind speed.

Measurements at different places show that the distribution of wind velocity over the year can be approximated by a Weibull-equation. This means that at least about 2/3 of the produced electricity will be earned by the upper third of wind velocity. From a mechanical point of view, the power density range increases by one thousand for a variation of wind speed of factor 10, thus producing a construction limit problem. Therefore, wind energy converters are constructed to harness the power from wind speeds in the upper regions.

1.4 MOMENTUM THEORY

Compared to the Rankine–Froude model, Blade element momentum theory accounts for the angular momentum of the rotor. Consider the left hand side of the figure below. We have a stream tube, in which there is the fluid and the rotor. We will assume that there is no interaction between the contents of the stream tube and everything outside of it.

That is, we are dealing with an isolated system. In physics, isolated systems must obey conservation laws. An example of such is the conservation of angular momentum. Thus, the angular momentum within the stream tube must be conserved. Consequently, if the rotor acquires angular momentum through its interaction with the fluid, something else must acquire equal and opposite angular momentum. As already mentioned, the system consists of just the fluid and the rotor, the fluid must acquire angular momentum in the wake.

As we related the change in axial momentum with some induction factor, we will relate the change in angular momentum of the fluid with the tangential induction factor. Let us consider the following setup. We will break the rotor area up into annular rings of infinitesimally small thickness. We are doing this so that we can assume that axial induction factors and tangential induction factors are constant throughout the annular ring. An assumption of this approach is that annular rings are independent of one another i.e. there is no interaction between the fluids of neighboring annular rings.

1.4.1 Bernoulli for rotating wake
Let us now go back to Bernoulli:

\[
\frac{1}{2} \rho v_1^2 + P_1 = \frac{1}{2} \rho v_2^2 + P_2
\]

The velocity is the velocity of the fluid along a streamline. The streamline may not necessarily run parallel to a particular co-ordinate axis, such as the z-axis. Thus the velocity may consist of components in the axes that make up the co-ordinate system. For this analysis, we will use cylindrical polar co-ordinates \((r, \theta, z)\) Thus 
\(v^2 = v_r^2 + v_\theta^2 + v_z^2\)

1.4.1.1 Pre-rotor

\[
P_\infty + \frac{1}{2} \rho v_u^2 = P_{b+} + \frac{1}{2} \rho v_D^2
\]

where \(v_u\) is the velocity of the fluid along a streamline far upstream, and is \(v_D\) the velocity of the fluid just prior to the rotor. Written in cylindrical polar co-ordinates, we have the following expression:

\[
P_\infty + \frac{1}{2} \rho v_u^2 = P_{b+} + \frac{1}{2} \rho v_D(1-a)^2
\]

where \(v_\infty\) and \(v_D(1-a)\) are the z-components of the velocity far upstream and just prior to the rotor respectively. This is exactly the same as the upstream equation from the Betz model.

It should be noted that, as can be seen from the figure above, the flow expands as it approaches the rotor, a consequence of the increase in static pressure and the conservation of mass. This would imply that \(v_r \neq 0\) upstream. However, for the purpose of this analysis, that effect will be neglected.

1.4.1.2 Post-rotor

\[
P_{D-} + \frac{1}{2} \rho v_D^2 = P_\infty + \frac{1}{2} \rho v_D^2
\]

where \(v_D\) is the velocity of the fluid just after interacting with the rotor. This can be written as 
\(v_D^2 = v_{D,r}^2 + v_{D,\theta}^2 + v_{D,z}^2\) The radial component of the velocity will be zero; this must be true if we are to

\[
P_{D-} + \frac{1}{2} \rho v_D^2 = P_\infty + \frac{1}{2} \rho v_D(1-a)^2
\]

In other words, the Bernoulli equations up and downstream of the rotor are the same as the Bernoulli expressions in the Betz model. Therefore, we can use results such as power extraction and wake speed that were derived in the Betz model i.e.

\[
v_{\infty, 1} = (1 - 2a) a \infty
\]

\[
\text{Power} = 2a(1 - a)^3 \rho A_D
\]

This allows us to calculate maximum power extraction for a system that includes a rotating wake. This can be shown to give the same value as that of the Betz model i.e. 0.59.

1.5 SABININ’ S THEORY

1.5.1 The impulse theory as applied to the horizontal shaft wind turbine.

The application of the impulse theory to the horizontal shaft wind turbine dimensioning has been taken over from the airplane propeller elastic theory, which, together with the classical whirlwind theory has led to highly efficient aerodynamic solutions.

One of the forerunners of this calculation and dimensioning method was G. K. Sabinin who had his studies in this field published starting from 1923.

1.5.2 Hypotheses:

The application of the impulse theory to the calculation and dimensioning of the propeller – type horizontal shaft turbines is based on the following main hypotheses:

1. the air jet crosses the rotor at an even velocity throughout the axial cross section;
(2) The rotor lets the air pass through the blades without determining a local velocity discontinuity and has an infinite number of blades;

(3) The presence of the rotor brings about a pressure variation between upstream and downstream, in a fluid domain delimited downstream the catching system by a cylindrical surface on which an infinite number of whose winding is the cylindrical surface corresponding to section A-A, fig. 2.1, downstream, in its immediate vicinity.

(4) The current tube delimited by the solenoid surface does not allow for the air exchange between its inside and outside, the air current passing through the rotor being considered isolated from the ambient.

(5) The current non-uniformity increases at the rotor outlet, which leads to turbulent energy losses and therefore to a lower efficiency of catching the wind energy, while the current twisting dissipated in alternating whirlpools caused by the instability of the flow downstream the rotor.

(6) Air pressure in the 0–0 cross-section in fig. 2.1 is assumed to be equal to the atmospheric one.

(7) In cross-section 1-1, pressure rises to values p1>p0, yet further increasing while aiming asymptotically towards values p0, far-off downstream.

(8) In the sections downstream the wind turbine rotor, pressure variation is neglected, considering that the centrifugal forces determined by the refined current twisting after rotor crossing are small as compared to the forces caused by the axial impulse in the same section.

(9) The pressure difference downstream and upstream the catching system leads to the occurrence of an axial force upon the rotor “Fa”; as a result of the adequately built rotor geometry there appears a tangential component “Fr” in the rotation plan, leading to the occurrence of the catching system useful moment. Obviously, wind-catching systems should be builder so that the rotor impulse tangential component should be as big as possible.

Fig. 1.6 schematically shows the air current shape upstream and downstream the rotor according to the above hypotheses, as well as the diagram of the modality the whirlwind solenoid surface is formed, delimiting the current tube downstream the rotor; upstream the rotor, current velocity V0 is equal to the far-off upstream velocity (infinite upstream); in the catching system rotor section 1-1, and as getting nearer and nearer to this section, the current axial velocity drops to values V1= V0 – V2, where V1 and V2 are velocities induced by the cylindrical turbulent layer generated by the whirlwinds on top of the rotor blades forming up a current tube.

As in the wind turbine rotor there appears a rotating moment in the section 1-1, that leads to the occurrence of the induced rotating impulse, counterclockwise to the catching system rotation. there results therefore that downstream the rotor, the air current rotates at a velocity equal to the velocity V2 in a close enough section, where the whirlwind tubes do not vicinity, the current peripheral velocity is considered not very much different from that, so that V2 ~ V2_, where V2 is the rotating velocity at the rotor outlet.

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**Fig 1.** formation of whirlwind solenoid surface Downstream the wind turbine
Determining of the peripheral force component and of the axial force component acting upon the catching system blade Isolating an annular area of \( r \) radius, \( dr \) thick, off the air current, the axial component \( dF_a \) as well as the rotation peripheral component \( dF_r \) can be determined in the corresponding annular section. These components lead to the occurrence of the interactions in the rotor construction elements (blades). By applying the impulse theorem and taking into account that, in keeping with second principle of mechanics, action is equal to reaction, there can be determined the reactions occurring in the rotor blades, along the axial and tangential directions, respectively,

\[
dm = 2\pi \cdot r \cdot \rho \cdot V_1 \cdot dr
\]

Where: \( dF_a \) – elementary axial force, and \( dF_r \) – the elementary tangential force

Where, \( D_m \) – is the unitary mass ir flow crossing the annular section in the rotor

\( V_1 = V_0 - V_1 \); \( V_1 \) is the induced velocity before the rotor, caused by the blades. By applying to the air mass delimited by the two concentric cylindrical areas of radius \( r \) and \( r + dr \),

\[
dF_a = V_2 dm;
\]

In a similar way, in keeping with theorem of the motional quantity moment, the elementary torque created by the tangential rotational force occurring on the elementary surface of the blades enclosed between the two cylindrical areas of radius \( r \) and \( r + dr \), there results the relation:

\[
dF_r = U_2 dm
\]

\( V_1, u_1, w_1 \), as well the corresponding velocities in a section downstream the rotor are written with the following relations: \( V_2 = -V_1 \),of the blades enclosed between the two cylindrical areas of radius \( r \) and \( r + dr \), there results the relation:

\[
\frac{u_2}{u_1} = \frac{(v_0 - v_1) \mu + (\alpha r + u_1)}{(v_0 - v_1) - \mu (\alpha r + u_1)}
\]

The relation represents the ratio of the axial induced velocity to the peripheral velocity component \( u_1 \). This ratio is variable along the blade from hub to apex. Relation is fulfilled provided what is in between the brackets is equal to zero. Out of this condition, there result:

\[
v_2 = \frac{v_1}{2} \quad \text{And} \quad u_2 = \frac{u_1}{2}
\]
UNIT- II WIND TURBINES

2.1 HAWT & VAWT:

The extraction device, named wind turbine rotor turns under the wind stream action, thus harvesting a mechanical power. The rotor drives a rotating electrical machine, the generator, which outputs are contain electrical power.

Several wind turbine concepts have been proposed over the years. A historical survey of wind turbine technology is beyond the scope here, but someone interested can find that in Ackermann (2005). There are two basic configurations, namely vertical axis wind turbines (VAWT) and, horizontal axis wind turbines (HAWT). Today, the vast majority of manufactured wind turbines are called horizontal axis, with either two or three blades.

HAWT is comprised of the tower and the nacelle, mounted on the top of the tower. Except for the energy conversion chain elements, the nacelle contains some control subsystems and some auxiliary elements (e.g., cooling and braking systems, etc.).

The energy conversion chain is organized into four subsystems:

i. aerodynamic subsystem, consisting mainly of the turbine rotor, which is composed of blades, and turbine hub, which is the support for blades;
ii. drive train, generally composed of: low-speed shaft – coupled with the turbine hub, speed multiplier and high-speed shaft – driving the electrical generator;
iii. electromagnetic subsystem, consisting mainly of the electric generator;
iv. Electric subsystem, including the elements for grid connection and local grid.

All wind turbines have a mechanism that moves the nacelle such that the blades are perpendicular to the wind direction. This mechanism could be a tail vane (small wind turbines) or an electric yaw device (medium and large wind turbines).
2.2 POWER DEVELOPED:

Wind turbines operate on a simple principle. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity.

Simply stated, a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines are used wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity. View the wind turbine animation to see how a wind turbine works or take a look inside.

Wind is a form of solar energy and is a result of the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and the rotation of the earth. Wind flow patterns and speeds vary greatly across the United States and are modified by bodies of water, vegetation, and differences in terrain. Humans use this wind flow, or motion energy, for many purposes: sailing, flying a kite, and even generating electricity.

2.3 THRUST:
Definition of thrust coefficient CT

Similarly to power coefficient CP, a thrust coefficient CT can be defined as a function of the axial induction factor and used to express the maximum thrust force upon the energy conversion device:

\[ C_T = \frac{\text{Thrust Force}}{\text{Dynamic Force}} = \frac{\sqrt{\rho \frac{V_1^2}{V_1^2 + 4ad(1-a)}}}{\sqrt{\rho V_1^2}} = \left[ \frac{4ad(1-a)}{4ad(1-a)} \right] \]

The thrust coefficient is not directly related to aerodynamic efficiency, but indirectly shows how much the energy extraction device affects the fluid flow (how much the fluid streamlines diverge due to fluid deceleration). CT is practically more helpful to evaluating the axial static load induced by the wind on the energy extraction device and thereafter dimensioning its structural support accordingly.

Fig. 2.3 Relationship between Wind Speed Vs Thrust Coefficient
2.4 EFFICIENCY

The word efficiency is used to describe precise measurable physical concepts as well as non-technical, or even poetic, concepts. The non-technical concepts for efficiency are subjective and impossible to define with formulas. For example, hear ballet reviewers say, “the dancer had a beautiful efficiency of movement divided by the coefficient of spandex times 23.69 times Pi”.

In terms of power, the formula, for just the turbine blade conversion efficiency (aerodynamic efficiency), will look like the expression below:

$$\text{Wind turbine efficiency} = \frac{\text{Shaft power out of turbine into gear box}}{\text{Wind power into turbine blades}}$$

For a wind turbine the available power is almost entirely from the kinetic energy of all those trillions upon trillions of air molecules moving along together in that mass movement of air molecules we call wind. Thus the expression for the bottom part of the fraction above would be the wind power formula also described in another page, and shown below:

$$\text{Power in the wind} = (\text{Density of air}) \times \left( \frac{2\pi \times \text{Velocity of wind} \times \text{Area of blade}}{\text{Diameter of blade}} \right)^2 \times C$$

2.5 ROTOR SELECTION-ROTOR DESIGN CONSIDERATIONS

There are several parameters involved in the design of an efficient economical wind turbine. Generally, efficient design of the blade is known to maximize the lift and minimize the drag on the blade. Now, minimization of the drag means that the aerofoil should face the relative wind in such a way that minimum possible area is exposed to the drag force of the wind. Furthermore the angle of this relative wind to the blades is determined by the relative magnitudes of the wind speed and the blade velocity.

The thing to note here is that the wind velocity basically stays constant throughout the swept area but the blade velocity increases from the inner edge to the tip. Which means the relative angle of the wind with respect to the blade is ever-changing. Now the various parameters which determine the design of the wind turbine are noted below:

2.5.1 Diameter of the Rotor:

Since the power generated is directly proportional to the square of the diameter of the rotor, it becomes a valuable parameter. It’s basically determined by the relation between the optimum power required to be generated by the mean wind speed of the area. Power generated, \(P=\eta \eta m C p P_0\)

2.5.2 Choice of the number of blades:

The choice of the number of blades of a wind rotor is critical to its construction as well as operation. Greater number of blades is known to create turbulence in the system, and a lesser number wouldn’t be able to capture the optimum amount of wind energy. Hence the number of blades should be determined by both constraints and after proper study of its dependence on the TSR. Now, let \(t_a\) be the time taken by one blade to move into the position previously occupied by the previous blade, so for an \(n\)-bladed rotor rotating at an angular velocity, \(\omega\) we have the following relation:

\[t_a = \frac{2\pi}{n \omega}\]

Again let \(t_b\) be the time taken by the disturbed wind, generated by the interference of the blades to move away and normal air to be reestablished. Now this will basically depend on the wind speed, on how fast or how slow the wind flow is. Hence it depends on the wind speed \(V\) & the length of the strongly perturbed wind stream, say \(d\) Here we have: \(t_b = \frac{d}{V}\)

For maximum power extraction, \(t_a\) & \(t_b\) should be equal, hence \(t_a = t_b\)

\[\frac{2\pi}{n \omega} = \frac{d}{V}, \quad d = \frac{2\pi V}{n \omega} \quad \text{d has to be determined empirically.}\]
2.5.3 Choice of the pitch angle:

The pitch angle is given by, \( \alpha = \theta - i \), where \( \theta \) is the angle between the speed of the wind stream and the speed of the blades. Now as \( \theta \) varies along the length of the blade, \( \alpha \) should also vary to ensure an optimal angle of incidence at all points of the blade. Thus the desirable twist along the blade can be calculated easily.

The pitch angle such as tan \( E \) or \( C_d/C_l \) should be minimum at all points of the rotor. Some researchers suggest the use of Eiffel polar plots, where the tangent to the Eiffel plot gives the minimum \( C_d/C_l \) for this situation. However for the same scale becomes inconvenient & as \( C_l \) is generally two orders of magnitude higher than \( C_d \) it’s better to plot a graph of \( C_d/C_l \) versus \( i \). Its minimum point will represent the optimal pitch angle.

2.5.4 Power Speed Characteristics

The mechanical power that can be extracted from the wind depends heavily on the wind speed, and for each wind speed is always an optimum turbine speed at which the wind power extracted at the shaft of the turbine is maximum, at any other speed apart from this optimum speed we get sub-standard operation of the system.

So our chief goal would be find out the optimum turbine speed over the operational range of the wind stream speeds. This thing is basically area specific, because the wind speeds would vary from place to place. Now the mechanical power transmitted at the shaft is:

\[
P = 0.5 C_p A \rho V_\infty^3
\]

As we know \( C_p \) is a function of the TSR & the pitch angle. For a wind turbine with radius \( R \), the above formula can be written as,

\[
P = 0.5 C_p \pi R^2 \rho V_\infty^3
\]

Now as the TSR, \( \lambda = \omega R/V_\infty \)

The maximum value of the shaft power output for any wind speed can be expressed as:

\[
P_m = 0.5 C_p \pi \left( \frac{R^5}{\lambda^3} \right) \omega^3 \rho
\]

\[
P_m \propto \omega^3
\]

2.5.5 Torque Speed Characteristics

Now we know that the Torque and power curves are related as follows:

\[
T_m = P_m/\omega
\]

Using the above value for \( P_m = 0.5 C_p \pi \left( \frac{R^5}{\lambda^3} \right) \omega^3 \rho \) We have,

\[
T_m = P_m/\omega
\]

\[
T_m = 0.5 C_p \pi \left( \frac{R^5}{\lambda^3} \right) \omega^2 \rho
\]

It is seen that at the optimum operating point on the \( C_p - \lambda \) curve, the torque is quadratically related to the rotational speed.

2.5.6 Solidity

The solidity of a wind rotor is defined as the ratio of the projected blade area to the area of wind intercepted. Generally the projected blade area doesn’t mean the actual blade area, it’s the blade area met by the wind or projected into the wind flow.

**Solidity ratio’s of various rotors**

<table>
<thead>
<tr>
<th>Type Of Rotor</th>
<th>Solidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savonius Rotor</td>
<td>1</td>
</tr>
<tr>
<td>Multi-blade water</td>
<td>0.7</td>
</tr>
<tr>
<td>pumping wind rotor</td>
<td></td>
</tr>
</tbody>
</table>
| High Speed Horizontal axis Rotor | 0.01 to 0.1 |}

2.6 TIP SPEED RATIO:

The tip speed ratio (TSR) of a wind turbine is defined as,

\[
\lambda = \frac{2\pi R N}{V_\infty}
\]

\( V_\infty \) = Speed of Wind without any rotor intervention
\( R = \) Radius of the Rotor, which signifies the swept area  
\( N = \) Rotational speed of the rotor in rps  
\( \lambda = \) Tip Speed Ratio

The tip speed ratio \( (\lambda) \) for wind turbines is the ratio between the rotational speed of the tip of a blade and the actual velocity of the wind. It’s basically non-dimensional in nature and high efficiency 3-blade turbines have tip speed ratios of 6–7.

2.7 NO. OF BLADES:

Modern wind turbine engineers avoid building large machines with an even number of rotor blades. The most important reason is the stability of the turbine. A rotor with an odd number of rotor blades (and at least three blades) can be considered to be similar to a disc when calculating the dynamic properties of the machine.

A rotor with an even number of blades will give stability problems for a machine with a stiff structure. The reason is that at the moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lowermost blade passes into the wind shade in front of the tower.

2.8 BLADE PROFILE:

The aerodynamic design of a wind turbine blade defines its width, thickness, direction and profile. It is a matter of finding the best compromise between air flow and strength (profile and structure). The purpose is to optimize performance while minimizing loads. At their very heart, wind turbine blades are very similar to airplane wings. By moving air across an airfoil surface, wind speed is higher across the curved surface, and lower across the flat surface.

![Fig. 2.4 Schematic of wind turbine blade](image)

2.9 POWER REGULATION:

Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are therefore generally designed to yield of maximum output at wind speeds around 15 meters per second. (30 knots or 33 mph).

Its does not pay to design turbines that maximize their output at stronger winds, because such strong winds are rare. In case of stronger wind is necessary to waste part of the excess energy of the wind in order to avoid the damaging wind turbine. All wind turbines are therefore designed with some sort of power control. There are two different ways of doing this safely on modern wind turbines.

2.9.1 Pitch Controlled Wind Turbines

![Fig. 2.5 Schematic of Pitch Controlled Wind Turbines](image)
On a pitch controlled wind turbine the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops again.

### 2.9.2 Stall Controlled Wind Turbines

(Passive) stall controlled wind turbines have the rotor blades bolted into the hub at a fixed angle. The geometry of the rotor blade profile however has been aerodynamically designed to ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the wind as shown in the picture on the previous page. This stall prevents the lifting force of the rotor blade from acting on the rotor.

If you have read the section on aerodynamics and aerodynamics stall, you will realise that as the actual wind speed in the area increases, the angle of attack of the rotor blade will increase, until at some point it starts to stall.

### 2.9.3 Active Stall Controlled Wind Turbines

An increasing number of larger wind turbines (1 MW and up) are being developed with an active stall power control mechanism.

Technically the active stall machines resemble pitch controlled machines, since they have patchable blades. In order to get a reasonably large torque (turning force) at low wind speeds, the machines will usually be programmed to pitch their blades much like a pitch controlled machine at low wind speeds. (Often they use only a few fixed steps depending upon the wind speed).

When the machine reaches its rated power, however, you will notice an important difference from the pitch controlled machines: If the generator is about to be overloaded, the machine will pitch its blades in the opposite direction from what a pitch controlled machine does. In other words, it will increase the angle of attack the rotor blades in order to make the blades go into a deeper stall, thus wasting the excess energy in the wind.

### 2.10 YAW CONTROL:

Turbines whether upwind or downwind, are generally stable in yaw in the sense that if the nacelle is free to yaw, the turbine will naturally remain pointing into the wind. However, it may not point exactly into wind, in which case some active control of the nacelle angle may be needed to maximize the energy capture.

Since a yaw drive is usually required anyway, e.g. for start-up and for unwinding the pendant cable, it may as well are used for active yaw tracking. Free yaw has the advantage that it does not generate any yaw moments at the yaw bearing. However, it is usually necessary to have at least some yaw damping, in which case there will be a yaw moment at the bearing. In practice, most turbines are used active yaw control.

A yaw error signal from the nacelle-mounted wind vane is then used to calculate a demand signal for the yaw actuator. Frequently the demand signal will simply command to yaw at a slow fixed rate in one or the other direction. The yaw vane signal must be heavily averaged, especially for upwind turbines where the vane is behind the rotor. Because of the slow response of the yaw control system, a simple dead-band controller is often sufficient. The yaw motor is switched on when the averaged yaw error exceeds a certain value, and switched off again, after a certain time or when the nacelle has moved through a certain angle.
More complex control algorithms are sometimes used, but the control is always slow-acting, and does not demand any special design considerations. One exception is the case of active yaw control to regulate aerodynamic power in high winds, as used on the variable speed Gamma 60 turbine.

This is clearly requires very rapid yaw rates, and results in large yaw loads and gyroscopic and asymmetric aerodynamic loads on the rotor. This method of power regulation would be too slow for a fixed-speed turbine, and even on the Gamma 60 the speed excursions during above-rated operation were quite large.

2.11 PITCH ANGLE CONTROL:
Pitch control is the most common means of controlling the aerodynamic power generated by the turbine rotor. It also has a major effect on all the aerodynamic loads generated by the rotor. In this control system changes the pitch angle of the plates according to the speed of the wind. below rated wind speed, the turbine should simply be trying to produce as much power as possible, so there is no need to vary the pitch angle.

![Fig. 2.7 Pitch Angle Control](image)

Here, the pitch setting should be optimum value to give maximum power. Above rated wind speed, pitch control provides a very effective means of regulating the aerodynamic power and loads produced by the rotor so that design limits are not exceeded. A decrease in pitch, i.e., turning the leading edge downwind, reduces the torque by increasing the angle of attack towards stall, where the lift starts to decrease and the drag increases. This is known as pitching towards stall.

These strategies will result in most of the blade being stalled in high winds. If only the blade tips are pitched, it may be difficult to fit a suitable actuator into the outboard portion of the blade; accessibility for maintenance is also difficult.

In the process of controlling the pitch in cases of speeds above the wind speed, the rotor output power decreases, generally the input variable to the pitch controller is the error signal arising from the difference between the output electrical power and the reference power. Generally the operation below the rated speed has the controller changing the pitch in a manner use the available wind stream most efficiently. The generator output has to be properly monitored, this would necessitate incorporation of better sensors, hence complete pitch control is generally not considered for smaller machines.

2.12 STALL CONTROL:
Many turbines are stall-regulated, blades are designed to stall in high winds without any pitch action being required. This means that pitch actuators are not required. Some means of aerodynamic braking is likely to be required, if only for emergencies. In order to achieve stall-regulation at reasonable wind speeds, the turbine must operate closer to stall than its pitch-regulated counterpart, resulting in lower aerodynamic efficiency below rated.

This disadvantage may be mitigated in a variable-speed turbine, when the rotor speed can be varied below rated in order to maintain peak power coefficient.
This means that the turbine can be operate further from the stall point in low winds, resulting in higher aerodynamic efficiency. However, this strategy means that when a gust hits the turbine, the load torque not only has to rise to match the wind torque but also has to increase further in order to slow the rotor down into stall. This removes is one of the main advantages of variable-speed operation, namely that it allows very smooth control of torque and power above rated.

2.13 SCHEMES FOR MAXIMUM POWER EXTRACTION:
Wind energy is one of the most promising renewable energy resources for producing electricity due to its cost competitiveness compared to other conventional types of energy resources. It takes a particular place to be the most suitable renewable energy resources for electricity production. It isn't harmful to the environment and it is an abundant resource available in nature. Hence, wind power could be utilized by mechanically converting in to the electrical power using wind turbine, WT. Various WT concepts have a quick development of wind power technologies and significant growth of wind power capacity during last two decades.

![Fig. 2.8 Schemes For Maximum Power Extraction](image)

Variable speed operation and direct drive WTs have been the modern developments in the technology of wind energy conversion system, WECS. Variable-speed operation has many advantages over fixed-speed generation such as increased energy capture, operation at MPPT over a wide range of wind speeds, high power quality, reduced mechanical stresses, aerodynamic noise improved system reliability, and it can provide (10-15) % higher output power and has less mechanical stresses in comparison with the operation at a fixed speed.

WTs can be classified according to the type of drive train into direct drive (DD) and gear drive (GD). The GD type uses a gear box, squirrel cage induction generator (SCIG) and classified as stall, active stall and pitch control.

The variable speed WT uses doubly-fed induction generator, (DFIG) especially in high power WTs. The gearless DD WTs have been used with small and medium size WTs employing permanent-magnet synchronous generator (PMSG) with higher numbers of poles to eliminate the need for gearbox which can be translated to higher efficiency.

PMSG appears more and more attractive, because the advantages of permanent magnet, (PM) machines over electrically excited machines such as its higher efficiency, higher energy yield, no additional power supply for the magnet field excitation and higher reliability due to the absence of mechanical components such as slip rings. In addition, the performance of PM materials is improving, and the cost is decreasing in recent years. Therefore, these advantages make direct-drive PM wind turbine systems more attractive in application of small and medium-scale wind turbines.

The TSR control method regulates the rotational speed of the generator to maintain an optimal TSR at which power extracted is maximum. For TSR calculation, both the wind speed and turbine speed need to be measured, and the optimal TSR must be given to the controller.
3.1 GENERATING SYSTEMS:

Wind energy is high on the governmental and institutional agenda. However, there are some stumbling blocks in the way of its widespread. Wind turbines come with different topologies, architectures and design features. Some options wind turbine topologies are as follows

- **Rotor** axis orientation: horizontal or vertical;
- **Rotor** position: upwind or downwind of tower;
- **Rotor** speed: fixed or variable;
- **Hub**: rigid, teetering gimbled or hinged blades;
- **Rigidity**: still or flexible;
- **Number** of blades: one, two, three or even more;
- **Power** control: stall, pitch, yaw or aerodynamic surfaces;
- **Yaw** control: active or free.

This chapter focuses only on horizontal-axis wind turbines (HAWTs), which are the prevailing type of wind turbine topology.

![Fig. 3.1 Generating Systems](image)

One of limiting factors in wind turbines lies in their generator technology. There is no consensus among academics and industry on the best wind turbine generator technology. Traditionally, there are three main types of wind turbine generators (WTGs) which can be considered for the various wind turbine systems, these being direct current (DC), alternating current (AC) synchronous and AC asynchronous generators.

In principle, each can be run at fixed or variable speed. Due to the fluctuating nature of wind power, it is advantageous to operate the WTG at variable speed which reduces the physical stress on the turbine blades and drive train, and which improves system aerodynamic efficiency and torque transient behaviors.

### 3.1.1 DC GENERATOR TECHNOLOGIES:

In conventional DC machines, the field is on the stator and the armature is on the rotor. The stator comprises a number of poles which are excited either by permanent magnets or by DC field windings. If the machine is electrically excited, it tends to follow the shunt wound DC generator concept.
An example of the DC wind generator system is illustrated in Fig. 6. It consists of a wind turbine, a DC generator, an insulated gate bipolar transistor (IGBT) inverter, a controller, a transformer and a power grid. For shunt wound DC generators, the field current (and thus magnetic field) increases with operational speed whilst the actual speed of the wind turbine is determined by the balance between the WT drive torque and the load torque. The rotor includes conductors wound on an armature which are connected to a split-slip ring commutator. Electrical power is extracted through brushes connecting the commutator which is used to rectify the generated AC power into DC output. Clearly, they require regular maintenance and are relatively costly due to the use of commutators and brushes.

In general, these DC WTGs are unusual in wind turbine applications except in low power demand situations [47; 23; 33; 54] where the load is physically close to the wind turbine, in heating applications or in battery charging.

3.2 CONSTANT SPEED CONSTANT FREQUENCY SYSTEMS: SCHEMES FOR WIND POWER GENERATION

Based on the speed and frequency, generally following schemes are identified:

3.2.1 CSCFS (Constant Speed Constant Frequency Scheme):

Constant speed drives are used for large generators that feed the generated power to the grid. Commonly synchronous generators or induction generators are used for power generation.

If the stator of an induction machine is connected to the power grid and if the rotor is driven above Synchronous speed, Ns, the machine delivers a constant line frequency (f=PNs/120) power to the grid. The slip of the generators is between 0 and 0.05. The torque of the machine should not exceed max. torque to prevent ‘run away’ (speed continues to increase unchecked).

Compared to synchronous generator, Induction generators are preferred because they are simpler, economical, easier to operate, control and maintain and have no synchronization problem. However, Capacitors have to be used to avoid reactive volt ampere burden on the grid.

In these types of turbines induction electrical machines (also known as asynchronous machines), generally used as motors for many industrial applications, are used for the conversion of the mechanical energy extracted from the wind into electrical energy. In the wind turbines, on the other hand, these electrical machines are used as generators, above all because of their constructional simplicity and toughness, their relative cost-effectiveness and for the simplicity of connection and
disconnection from the grid. The stator of an induction machine consists of copper windings for each phase, as the stator of synchronous machines.

On the contrary, the rotor in squirrel-cage motors has no windings, but consists of a series of copper bars set into the grooves of the laminated magnetic core. Some induction machines can have windings also on the rotor and in this case they are called wound rotor machines. They are expensive and less sturdy than the previous type and are used in variable-speed wind turbines, as better explained in the following paragraphs. Induction machines require a given quantity of reactive power to function.

This power shall be either drawn from the grid or delivered locally through a capacitor bank, which shall be properly sized so that self-excitation of the synchronous generator can be avoided in case of grid disconnection due to failure. Besides, these machines need an external source at constant frequency to generate the rotating magnetic field and consequently they are connected to grids with high short-circuit power able to support frequency.

When working as a generator, the asynchronous machine is speeded up by the wind rotor up to the synchronous speed and then connected to the grid, or it is at first connected to the grid and started as a motor up to the steady state speed. If the first starting method is used, the turbine clearly is self-starting and therefore the Pitch control must be present, whereas the second method is used for passive stall-regulated turbines.

In this case the control system stores the wind speed and defines the speed range within which the generator is to be started. Once the synchronous speed has been achieved, the wind power extracted makes the rotor run in hyper synchronous operation with negative slip, thus supplying active power to the grid.

As a matter of fact, since the slip has values in the order of 2%, the deviation from the rated speed is very limited and that’s why the use of these machines makes the wind turbine run at constant speed. To reduce the starting current, a soft starter is usually interposed between the asynchronous machine and the grid.

3.3 CHOICE OF GENERATING:

Wind is one of the renewable resources found in nature. Wind turbine is a device which converts kinetic energy of the wind into electrical energy. Horizontal axis wind turbine is the most used wind turbine now a day. Wind turbine is classified into two types. They are fixed speed turbines and variable speed turbines. In fixed speed turbines the maximum efficiency is obtained at a particular speed only. That is; regardless of the wind speed, the rotor speed of the wind turbine is fixed and it is determined by the gear ratio, frequency of the supply grid and design of the generator.

The device consists of an induction generator connected directly to the grid as shown in Figure 3.4.1. An installation of soft starter unit along with capacitor bank is necessary for reducing reactive power consumption. Fixed speed turbines are being simple, reliable, cheap, robust and well proven. And the cost of electrical parts are also low the disadvantages are, limited power quality control an uncontrollable reactive power consumption, and mechanical stresses due to fixed speed operation, all fluctuations in the wind speed are transmitted as fluctuations in mechanical torque and then it causes fluctuations in the electrical power on the grid. In Variable speed wind turbines the maximum efficiency is obtained over a wide range of wind speeds.
The electrical System designs of the variable speed wind turbines are more complicated as compared with fixed speed wind turbine. It is equipped with an induction or synchronous generator which connected to the grid through a power converter. The power converter is used to control the generator speed. The disadvantages of the fixed wind turbines are rectified in the variable speed wind turbine. The advantages are, increased energy capture, improved power quality, and reduced mechanical stress. The cost of the equipment is high and the design structure is complex are the disadvantages. Currently used the most popular variable-speed wind turbine configurations as shown in the figure 2. The structure of the paper is organized as following. Section II addresses the different types of generators that used in the wind turbine systems and its comparison. Then find out the best generator which is used in the wind turbine and converter operation are in section III. The advantages and disadvantages of the converter and compensation techniques are explained in section IV. Some concluding remarks are explained in section V.

![Variable speed wind turbine](image1)

**Fig. 3.4.2 Variable speed wind turbine**

### 3.3.1 Types Of Generators Used In Wind Turbine System

Any types of three-phase generator can connect to with a wind turbine. Several different types of generators which are used in wind turbines are as follows. Asynchronous (induction) generator and synchronous generator. Squirrel cage induction generator (SCIG) and wound rotor induction generator (WRIG) are comes under asynchronous generators. Wound rotor generator (WRSG) and permanent magnet generator (PMSG) are comes under synchronous generator.

#### 3.3.2 Asynchronous Generator

Squirrel Cage Induction Generator The fixed speed concept is used in this type of wind turbine. In this configuration the Squirrel Cage Induction Motor is directly connected to the wind through a transformer is shown in the figure 3. A capacitor bank is here for reactive power compensation and soft starter is used for smooth grid connection.

![Asynchronous Generator](image2)

**Fig. 3.5 Asynchronous Generator**
3.3.3 Wound rotor induction generator (WRIG)

The variable speed concept is used in this type. In this type of turbine Wound Rotor Induction Generator is directly connected to the grid as shown in the figure. The variable rotor resistance is for controlling slip and power output of the generator. The soft starter used here for reduce inrush current and reactive power compensator is used to eliminate the reactive power demand. The speed range is limited, poor control of active and reactive power, the slip power is dissipated in the variable resistance as losses are the disadvantages of this configuration.

![Fig. 3.6 Wound rotor induction generator](image)

3.3.4 Synchronous Generator

Turbine with wound rotor connected to the grid is shown in fig.4. This configuration neither require soft starter nor a reactive power comparator is its main advantage. The partial scale frequency converter used in the system will perform reactive power compensation as well as smooth grid connection. The wide range of dynamic speed control is depends on the size of frequency converter, the main disadvantage is that in the case of grid fault it require additional protection and use slip rings, this makes electrical connection to the rotor.

![Fig. 3.7 Wound Rotor Generator](image)

3.3.5 Permanent Magnet Generator

The generator is connected to the grid via full scale frequency converter. The frequency converter helps to control both the active and reactive power delivered by the generator to grid.

![Fig. 3.8 Permanent Magnet Generator](image)

3.3.6 Doubly Fed Induction Generator
In order to satisfy the modern grid codes, the grid turbine system have the capability of reactive power support. Doubly fed induction generator based wind turbine systems have more advantages than others. DFIG wind turbine deliver power through the stator and rotor of the generator the reactive power can provide in two sides. Hence use the term doubly. Reactive power can be supported either through grid side converter or through rotor side converter. The stator part of the turbine is directly connected to the grid and the rotor is interfaced through a crowbar and a power converter. The voltage to the stator part is applied from the grid and the voltage to the rotor is induced by the power converter. The power is delivered from the rotor through the power converter to the grid if the generator is operates above synchronous speed.

![Doubly Fed Induction Generator wind turbine](image)

**Fig. 3.9** Doubly Fed Induction Generator wind turbine

If the generator is operates below synchronous speed, then the power is delivered from the grid through the power converter to the rotor The power converter controls both the active and reactive power flow, the DC voltage of link capacitor between the grid and DFIG wind turbine by feeding the pulse width modules (PWM) to the converters.

A crowbar is implemented between the generator and converter to prevent short circuit in the wind energy system. This may result in high current and high voltage. The RSC converter controls the flux of the DFIG wind turbine . which operates at the slip frequency that depends on the rotor speed of the generator. According to the maximum active and reactive power control capability of converter, the power rating of the RSC is determined

### 3.4 DECIDING FACTORS

Wind turbine power production depends on interaction between the wind turbine rotor and the wind. The mean power output is determined by the mean wind speed, thus only steady-state aerodynamics have been considered to be important in this project and turbulence has been ignored. The first aerodynamic analyses of wind turbines were carried out by Betz [40] and Glauert [41] in the late 1920s and early 1930s. Power available in the wind is given by:

\[
P_{\text{wind}} = \frac{1}{2} \rho A V_{\text{wind}}^3
\]

In the above equation, \( \rho \) is air density, \( A \) is area swept by blades, and \( V_{\text{wind}} \) is wind speed. Betz proved that the maximum power extractable by an ideal turbine rotor with infinite blades from wind under ideal conditions is 59.26% (0.5926 times) of the power available in the wind. This limit is known as the Betz limit. In practice, wind turbines are limited to two or three blades due to a combination of structural and economic considerations, and hence, the amount of power they can extract is closer to about 50% (0.5 times) of the available power. The ratio of extractable power to available power is expressed as the rotor power coefficient \( CP \). The extractable power can thus be written as:

\[
P_{\text{wind}} = \frac{1}{2} C_P \rho A V_{\text{wind}}^3
\]

Modern utility-scale wind turbines use airfoils (shapes similar to an aircraft wing) to harness the kinetic energy in the wind. Two wind-induced forces act on the airfoil; lift and drag. Turbines
depend predominantly on lift force to apply torque to rotor blades, though some torque is caused by the drag force as well. The lift force is shown perpendicular to effective airflow direction; it is primarily responsible for the torque that rotates the rotor. The tips of the blades, being farthest from the hub, are responsible for the major part of the torque.

The advantages of stall-regulated wind turbines are that they are simple since no extra controllers are necessary. However, there is a considerable disadvantage: power that could have been captured is lost. The alternative strategy is known as blade pitching. In this strategy, a control system changes the angles of the tips of the rotor blades or rotates the entire blade to control the angle of attack and to control extracted power. Pitch-regulated wind turbines can extract more energy from similar wind regimes than non-pitch controlled machines, but require additional controllers and machinery, and increase complexity and cost. Fixed-speed wind turbines may be stall-regulated or they may employ blade pitching.

![Cross section of wind turbine blade airfoil (left) and relevant angles (right).](image)

3.5 SYNCHRONOUS GENERATING:

Synchronous generators are doubly fed machines which generate electricity by the principle of electromagnetic induction. The rotor is rotated by a prime mover. The result is a current, which flows in the stationary set of rotor conductors. Now this produces a magnetic field which in turn induces a current in the stator conductors. This is the current which we use finally as the output.

This rotating magnetic field induces an Alternating voltage, by the principle of electromagnetic induction, in the stator windings. Generally there are three sets of conductors distributed in phase sequence, so that the current produced is a three phase current. The rotor magnetic field is generally produced by means of induction, where we use either permanent magnets (in very small machines) or electromagnets in larger machines. Also the rotor winding is sometimes energized with direct current through slip rings and brushes. Sometimes even a stationary field winding, with moving poles in the rotor may be the source of the rotor magnetic field. Now this very setup is been used in automotive alternators, where by varying the current in the field winding we can change and control the alternator voltage generated. This process is known as excitation control. Basically the problem which plagues the electromagnets is the magnetization losses in the core, this is absent in the permanent magnet machines. This acts as an added advantage, but there is a size restriction owing to the cost of the material of the core.

3.5.1 ASYNCHRONOUS GENERATOR

Asynchronous generators or Induction generators are singly excited a.c. machine. Its stator winding is directly connected to the ac source whereas its rotor winding receives its energy from stator by means of induction. Balanced currents produce constant amplitude rotating mmf wave. The stator produced mmf and rotor produced mmf wave, both rotate in the air gap in the same direction at synchronous speed. These two mmf’s combine to give the resultant air-gap flux density wave of constant amplitude and rotating at synchronous speed. This flux induces currents in the rotor...
and an electromagnetic torque is produced which rotates the rotor. Asynchronous generators are mostly used as wind turbines as they can be operated at variable speed unlike synchronous generator.

### 3.6 SQUIRREL CAGE INDUCTION GENERATOR

A squirrel cage rotor is so named due to the shape which represents a cage like structure; it basically is the rotating part of the generator. Being cylindrical in nature, it's mounted on the shaft. The internal construction relates to the cage structure and contains longitudinal conductive bars (made of aluminum or copper) set into channel like constructs and connected together at both ends by shorting rings forming a proper cage-like shape. The core of the rotor is built of a stack of iron laminations, so as to decrease the eddy current losses.

![Fig. 3.12 Squirrel Cage rotor](image)

The current flowing in the field windings in the stator results in the setting up of a rotating magnetic field around the rotor. This magnetic field cuts across the shorted rotor conductors resulting in electromagnetic induction which induces a voltage and in turn a current in the rotor windings. The magnitude of both the induced entities depends directly on the relative speed of the rotor with respect to the stator; this quality is basically called the slip of the motor.

### 3.7 MODEL OF WIND SPEED:

Original models of wind turbines were fixed speed turbines; that is, the rotor speed was a constant for all wind speeds. Where the rotor is speed (in radians per second), is the length of a blade, and is the wind speed. That is to say, for a fixed-speed wind turbine, the value of the tip-speed ratio is only changed by wind speed variations.

![Fig. 3.13 Model of wind speed](image)

### 3.8 MODEL WIND TURBINE ROTOR:

A basic overview of common wind turbine systems currently in use is given in this chapter. Means of aerodynamic power control are shortly summarized, as well as wind turbine speed control and the control of reactive power exchanged with the connected grid.

Wind energy is gaining increasing importance worldwide. The processes of industrialization and economic development require energy. Fuels are the main energy resource in the world and are at the
center of the energy demands. Wind turbines using aerodynamic lift can be divided according to the orientation of the axis of rotation on the horizontal axis and vertical axis turbines. The horizontal axis or propeller-type approach currently dominates wind turbine applications. A horizontal axis wind turbine comprises a tower, a nacelle is mounted on top of the tower.

![Model Wind Turbine Rotor](image)

**Fig. 3.14 Model Wind Turbine Rotor**

### 3.9 DRIVE TRAIN MODEL:

The rotational motion of the turbine rotor is transmitted to the electrical generator by means of a mechanical transmission called drive train. Its structure strongly depends on each particular WECS technology. The speed multiplier dissociates the transmission in two parts: the low-speed shaft (LSS) on which the rotor is coupled and the high-speed shaft (HSS) relied on by the electrical generator. The coupling between the two shafts can be either rigid or flexible. In the second case, the LSS and HSS have different instantaneous rotational speeds. This kind of decoupling is used for damping the mechanical efforts generated either by wind speed or by electromagnetic torque variations. The result is a "compliant" and more reliable transmission, which is less affected by load transients and therefore by mechanical fatigue.

The technology used for speed multiplier construction is out of interest in this book, but one must note that the multiplying ratio depends mostly on the rated power and can generally involve more than one stage (e.g., based on spur or helical gears). The speed multiplier is critical equipment, severely affecting the WECS in terms of weight and reliability, and therefore overall efficiency.

![Drive Train Model](image)

**Fig. 3.15 Drive Train Model**

### 3.10 GENERATOR MODEL FOR STEADY STATE AND TRANSIENT STABILITY ANALYSIS:

While attempting to meet increase in demand, as a result of increasing environmental concern, more and more electricity is generated from renewable sources. One of the most popular ways of generating electricity from renewable sources is to use wind turbines. The need of extracting more power from the available wind power forces the application of different technologies in conversion systems.

#### 3.10.1 STEADY-STATE AND SMALL-SIGNAL BEHAVIOR

For power flow calculations, a wind plant can obviously be represented as a single generating unit at the interconnection substation. Determining the equivalent “reactive capability” of the plant, however, can be complicated since it will be a function of a large number of elements within the plant.
turbine reactive compensation, reactive losses in collector lines, auxiliary compensation equipment such as collector line capacitor banks, etc. While fairly standard and well-known for conventional generating units, this characteristic has not been considered explicitly for many of the plants developed over the past decade. Net reactive power is also a function of voltage if shunt capacitors are present as part of the plant reactive compensation scheme.

The dynamic nature of the wind resource can introduce a new dimension to power system studies, especially where the transmission interconnection is weak. Reactive power support for maintaining target voltages at the transmission interconnection will vary with the real power injected. Temporal variation of wind plant aggregate power is a very complicated function of a number of plant parameters and variables, but it also can be a defining factor for the dynamic characteristics of the reactive compensation system.

Additionally, the reactive compensation devices within the plant—turbines (shunt capacitors or advanced control), collector line capacitor bank, and possibly interconnect substation-based devices—are dynamic devices themselves, with set points and delay for toggling on or off of switched devices and continuous control for static var capabilities. Some of the factors that influence the variability of the aggregate production of a wind plant include:

- Variations in wind speed at each turbine location in the plant;
- Topographical features that introduce turbulence and shear into the moving air stream across the geographical expanse of the wind plant;
- The mechanical inertia of individual turbines, which influences how the wind speed variations, turbulence, and wind shear affect the output of individual turbines;
- The wind turbine control scheme, including the generator control and pitch regulation systems that determine how the electric power at the terminals of the turbine is influenced by fluctuating prime mover input;
- The number of turbines within the plant, since a larger number of turbines implies a larger geographical area for plant, and more statistical diversity in the local characteristics that contribute to output fluctuations;
- The grouping of turbines within the plant—if turbines are grouped into “strings”, rather than more uniformly distributed over the area of the plant, local fluctuations in wind speed will affect more than a single turbine at an instant of time. Wind generation is often characterized as “intermittent”, but, to better understand how it can impact power system operations, it is useful to consider the output variability in more detail.

Measurement data shows that the fluctuations on this time scale as a fraction of the plant rating decrease in magnitude as the number of turbines in the plant increases. Over longer time periods—tens of minutes to hours—wind plant generation will again exhibit fluctuation, and may also trend down or up as the larger scale meteorology responsible for the wind changes. Passage of a weather front is an example. Experience is showing that these trends can be predicted, but the accuracy of the prediction degrades quickly with time.

Forecasts for the next hour, for instance will be much better than those for several hours ahead. Longer-term forecasting for the next day or week is even less accurate, especially when timing is important. Predictions of a weather front passing an area tomorrow can be relatively accurate, but the accuracy for predicting which hour it will pass will be much lower. “Intermittent”, as the term is applied to wind generation, encompasses both the fluctuating characteristics along with the degree of uncertainty about when the resource will actually produce. Both of these attributes are important for power system engineers and operators who have come to understand well the fluctuations and uncertainties inherent in conventional generating resources and system loads.

Because wind generation is new, these characteristics are only beginning to be quantified, and procedure for dealing with them remained to be developed. As of this writing, there are no practical
analytical methods for characterizing the output fluctuations from a large wind plant. Direct measurements from operating wind plants are providing some important insights into the complicated interaction of the factors listed above. The National Renewable Energy Laboratory (NREL) launched a program in CY2000 to collect high-resolution electrical measurement data from operating wind plants across the U.S.

3.10.2 DYNAMIC RESPONSE

The electrical and mechanical technologies which comprise commercial wind turbines differ dramatically from the familiar synchronous generator and auxiliary systems that are used to represent almost all conventional generating equipment. And, instead of a small number of very large generating units, bulk wind plants can be made up of a very large number of relatively small machines. Until quite recently, these attributes have presented a difficult challenge to power system engineers engaged in evaluating transmission system impacts of large wind generation facilities. Evaluating the dynamic response of the electric power system during and immediately following major disturbances such as faults is a critical engineering function for ensuring system security and reliability. The magnitude of the main flux in the machine begins to decay in response to the reduced terminal voltage, and the position of the flux vector may suddenly change if there is a phase shift associated with the fault voltage

- The rotor power converter control instantaneously adjusts the quadrature axis rotor currents to “line up” with the new rotor flux vector.
- Since the rotor flux is not longer at the pre-fault value, the stator power of the machine is reduced accordingly. In response, the power converter control may try to increase the torque-producing component of rotor current.
- Because the electrical power output of the machine is now lower than the pre-fault value, there is net accelerating torque on the mechanical system which will increase the rotational speed of the machine.
- The increased rotational speed will cause the turbine blades to begin pitching to reduce the mechanical torque input to the machine and reduce speed. When the fault is cleared and the terminal voltage returns to near normal, the rotor power converter control will readjust the position of the rotor current vector to again line up with the rotor flux vector.
- Electric power output will jump back to (or slightly above, if the rotor current had been increased by the controller during the fault) the pre-fault value. Since mechanical power had been reduced by the pitch system, net decelerating torque on the mechanical system will cause rotational speed to decrease.
- The sudden changes in electromagnetic torque applied by the generator to the rotating shaft (at fault inception and clearing) excite the main mechanical resonance between the turbine blades and the generator inertia, such that these masses are now oscillating out of phase around the average speed of the rotating system.
- The oscillations in generator speed may be fed through the control system to produce oscillations in electric power at the stator terminals of the machine. While there are similarities to the response of a synchronous generator to the same disturbance, the markedly different equipment and control comprising the wind turbine lead to a different dynamic response.

There is agreement on a few general guidelines and principles for developing these dynamic equivalents. For remote disturbances – those originating on the transmission network, not within the wind plant itself – individual turbines can be considered coherent, i.e. they respond as if they were a large single machine of equivalent aggregate rating. And, as with the steady-state and small signal characterizations, the response of the plant in terms of reactive power may also be difficult to capture, unless the behavior at the interconnection bus bar is dominated by a single device such as a static var compensator located at the substation. Fortunately, most of these detailed questions are of likely of
secondary importance, especially where the focus is on the power system as a whole and not some particular aspect of the wind plant response. Until new research findings indicate otherwise, relatively simple dynamic equivalents consisting of a single or small number of equivalent machines at the interconnection substations is the recommended approach.

3.10.3 TRANSIENT

Dynamic simulations and studies of the interconnected power system are based on a number of assumptions that allow some simplifications in the representation of the dynamic components of the system. For some investigations, such simplifications are not valid or can obscure the aspects of the system model critical for the study. Studies of sub-synchronous torsional interaction, control interactions, inadvertent islanding, etc. may require models with more detail than those used for system dynamic studies. Full transient models of all but the simple wind turbine technologies require information and engineering detail that can only be obtained from the wind turbine manufacturer. Studies of these types should be conducted collaboratively with technical personnel from the turbine designer.

3.10.4 SHORT CIRCUIT CONTRIBUTIONS

Little guidance exists for calculating short-circuit contributions from large wind generation facilities. Analytical approaches are complicated for the following reasons:

- Commercial wind turbines employ induction machines for electromechanical energy conversion, which do not strictly conform to the standard procedures and assumptions used in calculation of short-circuit contributions on the transmission network.
- Generator control technologies employed in wind turbines—e.g. scalar or vector control of rotor current in a wound-rotor induction machine—can substantially modify the behavior of the induction machine in response to a sudden drop in terminal voltage, further complicating calculation of terminal currents during such conditions.
- Wind plants are composed of large numbers of relatively small generators, interconnected by an extensive medium-voltage network that itself influence fault contributions.
4.1 NEED OF VARIABLE SPEED SYSTEMS

There are many similarities in major components construction of fixed-speed wind turbines and wind turbines operating within a narrow variable-speed range. Fixed-speed wind turbines operating within a narrow speed range usually use a double-fed induction generator and have a converter connected to the rotor circuit. The rotational speed of the double-fed induction generator equally 1000 or 1500 rpm, so a gearbox implementation the required.

To simplify the nacelle design a direct-driven generator is used. A direct-driven generator using a large turbine blades diameter can operate at a very low speeds and does not need a gearbox installed to increase to speed.

The usage of frequency converter is needed to use a direct-driven generator, so wind turbines operating within a broad variable-speed range are equipped with a frequency converter. In an conventional fixed-speed wind turbine, the gearbox and the generator have to be mounted on a stiff bed plate and aligned precisely in respect to each other. A direct driven generator can be integrated with the nacelle, so the generator housing and support structure are also the main parts of the nacelle construction.

Nowadays, many wind turbines manufacturers are using variable speed wind turbine systems. The electrical system for variable speed operation is a lot more complicated, in comparison to fixed speed wind turbine system. The variable speed operation of a wind turbine can be obtained in many different ways with differentiation for a broad or a narrow wind speed range.

The main difference between wide and narrow wind turbines speed range is the energy production and the capability of noise reduction. A broad speed range gives larger power production and causes reduction of the noise in comparison to a narrow speed range system. One of the biggest advantages of variable speed systems controlled in a proper way is the reduction of power fluctuations emanating from the tower shadow.

4.2 POWER WIND SPEED CHARACTERISTICS

![Typical wind turbine power output with steady wind speed](image)

Fig.4.1 Typical wind turbine power output with steady wind speed
4.2.1 Cut-in speed

At very low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the **cut-in speed** and is typically between 3 and 4 metres per second.

4.2.2 Rated output power and rate output wind speed.

As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly as shown. However, typically somewhere between 12 and 17 metres per second, the power output reaches the limit that the electrical generator is capable of. This limit to the generator output is called the **rated power output** and the wind speed at which it is reached is called the **rated output wind speed**. At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. How this is done varies from design to design but typically with large turbines, it is done by adjusting the blade angles so as to keep the power at the constant level.

4.2.3 Cut-out speed

As the speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the **cut-out speed** and is usually around 25 metres per second.

4.2.4 Wind turbine efficiency or power coefficient

The available power in a stream of wind of the same cross-sectional area as the wind turbine can easily be shown to be

\[
C_p = \frac{P}{\frac{1}{2} \rho A v^3} = \frac{\frac{1}{2} \rho A v^3}{\frac{1}{2} \rho A v^3} = \frac{1}{\frac{1}{2} (1-a^2)(1+a)}
\]

If the wind speed \( U \) is in metres per second, the density \( \rho \) is in kilograms per cubic metre and the rotor diameter \( d \) is in metres then the available power is watts. The efficiency, \( \mu \), or, as it is more commonly called, the power coefficient, \( cp \), of the turbine is simply defined as the actual wind power delivered divided by the available power.

4.2.5 The Betz limit on wind turbine efficiency

There is a theoretical limit on the amount of power that can be extracted by a wind turbine from an airstream. It is called the Betz limit and the proof of this limit is given. The limit is

\[
\mu = \frac{16}{27} \approx 59\%
\]

4.3 VARIABLE SPEED CONSTANT FREQUENCY SYSTEMS

The evolution of wind power conversion technology has led to the development of different types of wind turbine configurations that make use of a variety of electric generators. A classification of most common electric generators in large wind energy conversion systems (WECS) is presented in Figure 4.2.
The wound-rotor induction generator, also known as the doubly fed induction generator (DFIG), is one of the most commonly used generators in the wind energy industry. The wound-rotor synchronous generator (WRSG) is also found in practical WECSs with high numbers of poles operating at low rotor speeds. Squirrel-cage induction generators (SCIGs) are also widely employed in wind energy systems where the rotor circuits (rotor bars) are shorted internally and therefore not brought out for connection with external circuits. In permanent-magnet synchronous generators (PMSGs), the rotor magnetic flux is generated by permanent magnets. Two types of PMSG are used in the wind energy industry: surface mounted and inset magnets.

### 4.4 SYNCHRONOUS GENERATORS

In wind energy applications, synchronous generators are used in variable speed systems only. The converter to decouple the frequency between machine and grid has to be designed for full load, different from the doubly-fed induction generator concept. Generators of larger ratings are generally equipped with an excitation winding, fed via slip-rings from a separate exciter.

Synchronous machines are more suitable for designs with large pole numbers than induction machines. Hence they are the option for direct driven generators, sparing the gear box in the system. Generators of considerable diameter and pole number values are found in the gearless Magawatt systems.

The conventional synchronous generator can be used with a very cheap and efficient diode rectifier. The synchronous generator is more complicated than the induction generator and should therefore be somewhat more expensive. However, standard synchronous generators are generally cheaper than standard induction generators. A fair comparison cannot be made since the standard induction generator is enclosed while the synchronous generator is open-circuit ventilated. The low cost of the rectifier as well as the low rectifier losses make the synchronous generator system probably the most economic one today. The drawback of this generator and rectifier combination is that motor start of the turbine is not possible by means of the main frequency converter.
4.5 SYNCHRONOUS GENERATOR AND DIODE-TYRISTOR CONVERTER

The generator system discussed in this report is a system consisting of a synchronous generator, a diode rectifier, a dc filter and a thyristor inverter. The inverter may have a harmonic filter on the network side if it is necessary to comply with utility demands. The harmonic filter is, however, not included in the efficiency calculations in this report. Figure 1.6 shows the total power generating system.

The advantage of a synchronous generator is that it can be connected to a diode or thyristor rectifier. The low losses and the low price of the rectifier make the total cost much lower than that of the induction generator with a self-commutated rectifier [5]. When using a diode rectifier the fundamental of the armature current has almost unity power factor. The induction generator needs higher current rating because of the magnetization current. The disadvantage is that it is not possible to use the main frequency converter for motor start of the turbine. If the turbine cannot start by itself it is necessary to use auxiliary start equipment. If a very fast torque control is important, then a generator with a self-commutated rectifier allows faster torque response. A normal synchronous generator with a diode rectifier will possibly be able to control the shaft torque up to about 10 Hz, which should be fast enough for most wind turbine generator systems.

4.6 DOUBLY-FED INDUCTION GENERATORS (DFIG)

The most common variable-speed wind turbines are the Doubly Fed Induction Generator (DFIG), which offers high efficiency over a wide range of wind speeds as well as the ability to supply power at a constant voltage and frequency while the rotor speed varies. This technology consists of a wound rotor induction generator and a back-to-back power converter placed into the rotor of the machine while the stator is directly connected to the grid.

The power converter allows for the machine to be controlled between sub-synchronous speed and super-synchronous speed (a speed higher than the synchronous speed), usually, a variation from -40% to -30% of synchronous speed is chosen. This converter capacity is designed to handle 20–30% of the machine rate, which is beneficial both economically and technically. The rotor of the DFIG has a three-phase winding similar to the stator winding. The rotor winding is embedded in the rotor laminations but in the exterior perimeter. This winding is usually fed through slip-rings mounted on the rotor shaft. In DFIG wind energy systems, the rotor winding is normally connected to a power converter system that makes the rotor speed adjustable.

The fact that the rotor circuit of an SCIG is not accessible can be changed if the rotor circuit is wound and made accessible via slip rings, which offers the possibility of controlling the rotor circuit so that the operational speed range of the generator can be increased in a controlled manner. The rotor circuit is often connected to back-to-back power electronic converters, which consists of a rotor-side converter and a grid-side converter sharing the same DC bus, so that the difference between the mechanical speed of the rotor and the electrical speed of the grid can be compensated via injecting a current with a variable frequency into the rotor circuit. Hence, the operation during both normal and faulty conditions can be regulated by controlling the converters.

![DFIG Diagram](diagram.png)

Figure 4.4 Double fed induction generator
The doubly fed induction machine (DFIM), doubly fed induction generator (DFIG), or wound rotor induction generator (WRIG) are common terms used to describe an electrical machine with the following characteristics:

- A cylindrical stator that has in the internal face a set of slots (typically 36–48), in which are located the three phase windings, creating a magnetic field in the air gap with two or three pairs of poles.
- A cylindrical rotor that has in the external face a set of slots, in which the three phase windings, are to chafed creating a magnetic field in the air gap of the same pair of poles as the stator.

The magnetic field created by both the stator and rotor windings must turn at the same speed but phase shift to some degrees as a function of the torque created by the machine.

As the rotor is a rotating part of the machine, to feed it, it’s necessary to have three slip rings. The slip ring assembly requires maintenance and compromises the system reliability, cost, and efficiency.

A DFIG can be excited via the rotor windings and does not have to be excited via the stator windings. If needed, the reactive power needed for the excitation from the stator windings can be generated by the grid-side converter.

As a result, a wind power plant equipped with DFIGs can easily take part in the regulation of grid voltage. The stator always feeds real power to the grid but the real power in the rotor circuit can flow bidirectional, from the grid to the rotor or from the rotor to the grid, depending on the operational condition. Ignoring the losses, the power handled by the rotor circuit is

\[ P_{\text{rotor}} = -s \cdot P_{\text{stator}}. \]

Where \( s \) is the slip, and the power sent to the grid is

\[ P_{\text{grid}} = P_{\text{rotor}} + P_{\text{stator}} = (1 - s)P_{\text{stator}}. \]

Since most of the power flows through the stator circuit, the power processed by the rotor circuit can be reduced roughly to 30%. This means the great advantage of a sufficient range of operational speed can be achieved at a reasonably low cost.

DFIGs are often applied in variable speed wind turbine systems with a multi-stage gearbox. Its basic operating principle is the same as an SCIG-based system but the rotor active power is controlled by the power electronic converters so that a speed range of ±30% around the synchronous speed can be obtained. The choice of the rated power for the rotor converter is a trade-off between cost and the desired speed range. Moreover, the converter compensates the reactive power and smooth’s the grid connection.

Although a DFIG offers a sufficient range of operational speed and many other merits, it is very sensitive to voltage disturbances, especially voltage sags. Abrupt voltage drops at the terminals often cause large voltage disturbances on the rotor, which may exceed the voltage rating of the rotor-
side converter (RSC), make the rotor current uncontrollable, and even damage the RSC. Many strategies are available to improve the low-voltage ride-through capability of DFIGs.3

### 4.7 SQUIRREL-CAGE INDUCTION GENERATORS (SCIG)

Squirrel-cage induction generators are exclusively used in the fixed-speed WECS. The generator power rating is in the range of a few kilowatts to a few megawatts. For large wind farms, megawatt generators are widely employed. The squirrel-cage induction generator is simple, reliable, cost-effective, and maintenance-free compared to other types of wind generators. This is achieved by using a robust squirrel-cage rotor structure, in which the rotor winding is made of copper bars embedded in the rotor magnetic core. As a result, slip rings and brushes that are required in the wound-rotor induction and synchronous generators are eliminated.

There are two main types of induction generators in the wind energy industry: doubly fed induction generators (DFIGs) and squirrel-cage induction generators (SCIGs). These generators have the same stator structure and differ only in the rotor structure. Figure shows the construction of a squirrel-cage induction generator. The stator is made of thin silicon steel laminations. The laminations are insulated to minimize iron losses caused by induced eddy currents. The laminations are basically flat rings with openings disposed along the inner perimeter of the ring. When the laminations are stacked together with the openings aligned, a canal is formed, in which a three-phase copper winding is placed.

The rotor of the SCIG is composed of the laminated core and rotor bars. The rotor bars are embedded in slots inside the rotor laminations and are shorted on both ends by end rings. When the stator winding is connected to a three-phase supply, a rotating magnetic field is generated in the air gap. The rotating field induces a three-phase voltage in the rotor bars. Since the rotor bars are shorted, the induced rotor voltage produces a rotor current, which interacts with the rotating field to produce the electromagnetic torque.

A simplified diagram of the induction generator is shown in Figure 4.6, where the multiple coils in the stator and multiple bars in the rotor are grouped and represented.

![Fig. 4.6 Simplified diagram of the induction generator](image)

There are two commonly used dynamic models for the induction generator. One is based on space vector theory and the other is the \(dq\)-axis model derived from the space vector model. The space vector model features compact mathematical expressions and a single equivalent circuit but requires complex (real and imaginary part) variables, whereas the \(dq\)-frame model is composed of two equivalent circuits, one for each axis.

These models are closely related to each other and are equally valid for the analysis of transient and steady-state performance of the induction generator. A squirrel-cage induction machine is often operated as a motor but it can be operated as a generator when driven by a prime mover to a speed exceeding the synchronous speed. Induction machines are widely applied as generators in wind power applications due to the reduced unit cost and size, ruggedness, lack of brushes, absence of a
An induction generator produces real power but it needs reactive power to establish the excitation (the magnetic field). This leads to a low power factor, which is often penalized by utility companies. The reactive power needed for excitation can be provided by a capacitor bank, the grid or a solid-state power electronic converter. The connection of an SCIG, in particular a big one, to the grid often causes a large inrush current that is 7 ~ 8 times of the rated current and a soft-starter is often needed. The pole pair number of SCIG used in commercial fixed-speed wind turbines is often equal to 2 or 3, which corresponds to a synchronous speed of 1500 rpm or 1000 rpm for a 50 Hz system. As a result, a three-stage gearbox is often required in the drive train. SCIGs are often applied in fixed-speed wind turbine systems directly connected to the grid through a transformer, as shown in Figure.

The need for a three-stage gearbox in the drive train considerably increases the weight of the nacelle, and the investment and maintenance costs. Moreover, it is necessary to obtain the excitation current from the grid, which makes impossible to support the grid voltage.

4.8 VARIABLE SPEED GENERATORS MODELLING
The complete generator system and its main components are shown in Figure 2.1. The turbine is described by its power $P_t$ and speed $n_t$. The speed is raised to the generator speed $n_g$ via a gear. $P_g$ is the input power to the generator shaft. The generator can be magnetized either directly by the field current $I_f$ fed from slip rings or by the exciter current $I_E$. The exciter is an integrated brushless exciter with rotating rectifier. The output electrical power from the generator armature is denoted by $P_a$. The generator armature current $I_a$ and voltage $U_a$ are rectified by a three-phase diode rectifier.
The rectifier creates a dc voltage $U_{dr}$ and a dc current $I_{dr}$. On the other side of the dc filter the inverter controls the inverter dc voltage $U_{di}$ and dc current $I_{di}$. $U_d$ is the mean dc voltage and $I_d$ is the mean dc current. The power of the dc link $P_d$ is the mean value of the dc power, equal to $I_d U_d$. The inverter ac current is denoted $I_i$ and the inverter ac voltage $U_i$. The ac power from the inverter is denoted $P_i$.

![Fig. 4.9 The total system and the quantities used. The generator can be magnetized either by slip rings or by an integrated exciter.](image)

The filter is used to take care of the current harmonics by short circuiting the major part. The output of the generator system is the network current $I_{\text{net}}$. The network voltage is denoted $U_{\text{net}}$.

### 4.4.1 Drive Selection

The variable-speed operation can capture theoretically about one-third more energy per year than the fixed-speed system. The actual improvement reported by the variable-speed systems operators in the field is lower, around 20 to 35 percent. However, the improvement of even 15 to 20 percent in the annual energy yield by variable-speed operation can make the systems commercially viable in low wind region. This can open a whole new market for the wind-power installations, and this is happening at present in many countries. Therefore the newer installations are more likely to use the variable-speed systems. As of 1997, the distribution of the system design is 35 percent one fixed speed, 45 percent two fixed-speed and 20 percent variable-speed power electronics systems. How waver the market share of the variable-speed systems, however, is increasing every year.

### 4.9 VARIABLE SPEED VARIABLE FREQUENCY SCHEMES (VSVFS)

This scheme is suitable for loads that are frequency insensitive such as heating load.
Depending upon the wind speed, squirrel cage Induction Generator generates power at variable frequency. Such generators are excited by Capacitor-bank. The magnitude and frequency of the generated emf depends upon the wind turbine speed, excitation capacitance and load impedance. If load requires constant dc voltage, output of generators is converted into d.c. using chopper controlled rectifiers. Feedback system can be used to monitor and control to get desired performance.

4.5.1 Advantages of the Variable Speed WECS with Respect to the Constant Speed WECS
1. For the same turbine WECS variable speed allows higher power capture, thereby increasing the annual energy output significantly.
2. The variable speed WECS is capable of providing the required reactive power of the induction generator from the dc bus capacitance.
3. Variable speed operation also allows a standard single winding machine to be used over the entire operating range of the turbine.
4. In variable speed WECS since torque of the machine is controlled (either by field-orientation or direct torque control) the generator cannot be overloaded at any point of time beyond the prescribed limits.

4.5.2 Disadvantages of Variable Speed WECS with respect to the Constant Speed WECS
1. The power rating of the generator in the variable speed scheme should be five times greater than that of the optimal version of the constant speed case.
2. Operating the generator over a wide speed range may result in a considerable reduction in the overall efficiency of the energy conversion process.
UNIT V- GRID CONNECTED SYSTEMS

5.1 WIND INTERCONNECTION REQUIREMENTS

- on and operation for generating plants
- In general, applicable for all kind of generating plants as well as WPP’s
- Requirements – apply normally at a defined reference point of the generating plant

5.1.1 Connection requirements can be split into different groups

- General requirements (e.g. definitions, MW size limits, reference points) • Req. on steady state operation (e.g. operation ranges, power quality)
- Req. on dynamic performance -- different control schemes -- during grid faults
- Communication (e.g. SCADA), protection and verification (e.g. protection settings at WT, WPP level)
- Req. on simulation models / validation
- Compliance of WPP with requirements(type tests / certification, WPP compialce tests / monitoring)
- "Additional requirement"

5.1.2 Interconnection Requirements – Challenges

- Problems for the wind industry (e.g. manufacturers, developers, operators):
- Requirements changing quite frequently (e.g. updates and drafting of new rules) • Requirements are diverse and sometimes that contain technical gray zones
- It must be fully clear what is required and what has to be fulfilled by the WPP at which reference point
- A common specification language is missing

5.2 LOW-VOLTAGE RIDE THROUGH (LVRT)

LVRT (Low Voltage Ride Through – also known as FRT - Fault Ride Through) has become a crucial feature of the wind turbine control system. The LVRT-term is capturing the ability of a wind turbine (or in reality a wind park) to stay connected to the grid throughout a short mains voltage drop (a brownout) or a mains failure (a blackout).

When the voltage of the grid is dropping it is essential that a wind park stay online in order to prevent major blackouts. It is not only essential that the park stays online - it is equally essential that the park is working actively to compensate for the faulty grid condition.

In China major blackouts (as a result of entire wind parks tripping and getting offline as a result of a brownout) have been seen.

This has increased the focus of the LVRT feature of the wind turbine control system. It is a fact that many wind turbine control systems installed just a few years ago does not have the LVRT-feature - and cannot upgrade to an economical way- for the grid operator - acceptable performance.

That is why DEIF Wind Power Technology in close cooperation with the power converter supplier is enjoying a drastically increased interest for our control systems - not only for new installed turbines, but also for upgrading existing installed capacity. Laboratory testing as early as 2010 brought the proof-of-concept which has later been full-scale implemented.

We are proud of having got several wind parks controlled by our control solutions full-scale field tested and approved as being in full LVRT-feature compliance by Chinese grid-operators. Whether the LVRT capability of a wind farm is satisfying for meeting the requirements is defined in
grid codes issued by the grid operator. The capability of meeting these demands is decisive for whether the wind turbine/the wind park is allowed to be connected to the grid.

5.2.1 Examples of LVRT demands to the wind park (and derived from that – to the individual wind turbines) are;

- for short system faults (lasting up to 140ms) the wind farm has to remain connected to the grid. For supergrid (HV-grids) voltage dips of longer durations the wind farm has to remain connected to the grid up to more than 3 minutes
- During grid faults or brownouts a wind farm has to supply maximum reactive current to the grid without exceeding the transient rating of the plant
- On super-grids during voltage dips lasting more than 140ms the active power output of a wind farm has to be retained at least in proportion to the retained balanced supergrid voltage

As mentioned above the LVRT-demands are individually specified by the grid operators and might therefore vary from operator to operator and from country to country. For wind turbines the LVRT testing is described in the standard IEC 61400-21. The LVRT-feature of wind turbine controls from DEIF WPT in combination with our Park Power Management solutions (including our forecasting solution) is all a wind park owner need to be in perfect compliance with the demands of grid operators worldwide.

5.3 RAMP RATE LIMITATIONS

The ramp rate of wind power output is defined as the power changes from minute to minute, so its unit is [MW/minute]. Some ramp events result in severe ramp rates of power generation that exceed a “ramp rate limit” (RRL), which represents the capability of the remaining power system to compensate for wind ramps.

Those ramp events, such as the sudden die-off and rise, not only disturb the balance of demand and supply, but also hamper the participation of wind power in the electricity market. Wind power curtailment and reserve services can reduce severe ramp events, but they waste potential wind power energy and increase the thermal generation costs, respectively. Recently, a battery has been used to limit severe ramp events.

A battery can be charged during ramp-up events and discharged when ramp-down events without either wasting energy (except for energy loss in round trip charging and discharging of the battery) or requiring reserve services.

The use of batteries can also help stakeholders maximize profits by arbitraging electricity prices. However, the power rating, battery capacity, and operation policies must be designed before establishing a battery system. Therefore, the goal of this paper is to design battery parameters in order to compensate almost all severe ramp events of wind power output.

5.4 SUPPLY OF ANCILLARY SERVICES FOR FREQUENCY AND VOLTAGE CONTROL

Controlling frequency and voltage has an essential part of operating a power system. However, since the liberalization of the electricity supply industry, the resources required to achieve this control have been treated as services that the system operator has to obtain from other industry participants.

Because this liberalization has proceeded independently in different parts of the world and because of the structural differences in the underlying power systems, the technical definitions of these services and the rules governing their trading vary considerably.

5.4.1 Frequency Control Services

Maintaining the frequency at its target value requires that the active power produced and/or consumed be controlled to keep the load and generation in balance. A certain amount of active power, usually called frequency control reserve, is kept available to perform this control. The positive frequency control reserve designates the active power reserve used to compensate for a drop in frequency. On the other hand, the deployment of negative frequency control reserve helps to decrease the frequency.
Three levels of controls are generally used to maintain this balance between load and generation. Primary frequency control is a local automatic control that adjusts the active power generation of the generating units and the consumption of controllable loads to restore quickly the balance between load and generation and counteract frequency variations.

In particular, it is designed to stabilize the frequency following large generation or load outages. It is thus indispensable for the stability of the power system. All the generators that are located in a synchronous zone and are fitted with a speed governor perform this control automatically. The demand side also participates in this control through the self-regulating effect of frequency-sensitive loads such as induction motors or the action of frequency-sensitive relays that disconnect or connect some loads at given frequency thresholds.

However, this demand-side contribution is not always taken into account in the calculation of the primary frequency control response. The provision of this primary control is subject to some constraints. Some generating units that increase their output in response to a frequency drop which cannot sustain this response for an indefinite period of time.

Their contribution must therefore be replaced before it runs out. It is also important that the contributors to primary control be distributed across the interconnected network to reduce unplanned power transits following a large generation outage and enhance the security of the system. In addition, a uniform repartition helps to maintain the stability of islanded systems in case of a power system separation.

Secondary frequency control is a centralized automatic control that adjusts the active power production of the generating units to restore the frequency and the interchanges with other systems to their target values following an imbalance. In other words, while primary control limits stops frequency excursions, secondary control brings the frequency back to its target value. Only the generating units that are located in the area where the imbalance originated should participate in this control as it is the responsibility of each area to maintain its load and generation in balance.

Note that loads usually do not participate in secondary frequency controls. Contrary to primary frequency control, frequency secondary control is not indispensable. This control is thus not implemented in some power systems where the frequency is regulated using only automatic primary and manual tertiary control. However, secondary frequency control is used in all large interconnected systems because manual control does not remove overloads on the tie lines quickly enough. Within the UCTE, secondary frequency control is also called load-frequency control (LFC).

5.4.2 Voltage Control Service

From a system perspective, the overall task of regulating the voltage is sometimes organized into a three-level hierarchy. Primary voltage control is a local automatic control that maintains the voltage at a given bus (at the stator in the case of a generating unit) at its set point. Automatic voltage regulators (AVRs) fulfill this task for generating units. Other controllable devices, such as static voltage compensators, can also participate in this primary control.

Secondary voltage control is a centralized automatic control that coordinates the actions of local regulators in order to manage the injection of reactive power within a regional voltage zone. This uncommon technology is used in France and Italy. Tertiary voltage control refers to the manual optimization of the reactive power flows across the power system.

In practice, because of the close link between voltage and reactive power in transmission networks, these three levels of control require that participating devices are able to generate or absorb reactive power. From the perspective of providers of voltage control services, it is convenient to divide the production of reactive power into a basic and an enhanced reactive power service. The basic or compulsory reactive power service encompasses the requirements that generating units must fulfill to be connected to the network.

The enhanced reactive power service is a non-compulsory service that is provided on top of the basic requirements. The terminology of voltage control is much more uniform than for frequency control and does not need to be discussed further.
5.5 CURRENT PRACTICES AND INDUSTRY TRENDS WIND INTERCONNECTION

Wind power has become the world’s fastest growing renewable energy source. Many benefits of the wind energy are environmental protection, economic development, diversity of the supply, rapid spread, transference and technological innovation, industrial scale electricity in network and the fact is that the wind does not pollute, it is abundant, free and unlimited. The world-wide wind power installed capacity has exceeded 120 GW and the new installation in 2008 alone was more than 27 GW. More than thousands of wind turbines operating, with a total nameplate capacity of 121,188 MW of which wind power in Europe accounts for 55% (2008).

World wind generation capacity more than quadrupled between 2000 and 2006, doubling about every three years. 81% of wind power installations are in the US and Europe.

Wind power is often described as an “intermittent” energy source, and therefore unreliable. In fact, at power system level, wind energy does not start and stop at regular intervals, so the term “intermittent” is misleading. The output of aggregated wind capacity is variable, just as the power system itself is inherently variable. In the past, wind turbine generators were disconnected from the system during faults.

Nowadays, there is an increasing requirement for wind farms to remain connected to the power system during faults, since the wind power lost might affect the system stability. Therefore, the wind turbine behavior during system performance and its influence in the system protection must be analyzed. One of the most frequent irrelevant features about integrating wind energy into the electricity network is that it is treated in isolation.

An electricity system in practice is modify like a massive bath tub, with hundreds of taps (power stations) providing the input and millions of plug holes (consumers) draining the output. The taps and plugs are always open and close. For the grid operators, the task is to make sure there is enough water in the tub to maintain system security. It is therefore the combined effects of all technologies, as well as the demand patterns, that matters. The specific nature of wind power as a distributed and variable generation source requires specific infrastructure investments and the implementation of new technology and grid management concepts.

High levels of wind energy in system can impact on grid stability, congestion management and transmission efficiency and transmission adequacy. A grid code covers all material technical aspects relating to connections to, and the operation and use of, a country’s electricity transmission system. They lay down rules which define the ways in which generating stations connecting to the system must operate in order to maintain grid stability.

5.6 IMPACT ON STEADY-STATE AND DYNAMIC PERFORMANCE OF THE POWER SYSTEM INCLUDING MODELING ISSUE

5.6.1 Modeling for steady state analysis

The power system modeling including wind turbines for steady state analysis in PSS/E version 32 is fairly simple. Each individual wind turbine generator (WTG) is connected to a 690V bus and the WTGs are connected to the wind farm internal network through their 0.69/35 kV step-up transformers. The internal network is organized in eight rows or sections with five WTGs in each section. Within these rows, the wind turbines are connected through 35kV underground cables of different lengths and capacities depending on the location of each unit and the distance to the 35kV collector bus.

The load flow solution provides the initial conditions for subsequent dynamic simulations. The maximum and minimum limits of active and reactive power must be respected in order to achieve a successful initialization. Inconsistencies between the power flow and the dynamic model will result in an unacceptable initialization.

5.6.2 Modeling for dynamic analysis
Initial dynamic model data file for the regional Power System is used for the study case. The dynamic data file so called dyr.file in PSS/E consist of dynamic parameter data for all conventional synchronous generators, turbines, exciters governors and other devices. The first step in dynamic simulation using initial dynamic file is to enter the detailed dynamic model data for Wind Farm, which is saved in a file.

This file contains a group of records, each of which defines the location of a dynamic WTG model in the grid along with the constant parameters of the model. The model includes generator, electrical control, wind turbine, and pitch control.

Dynamic simulation is performed based on the load flow data that provide the transmission grid, load, and generator data. In this study, a number of simulations are performed to investigate the WTGs model response subjected to grid disturbances. The most relevant disturbance for the study case is a three-phase symmetrical short-circuit fault on the 110kV interconnection bus. Additional fault events are simulated on the different busses of the Kosovo Transmission System to evaluate WTG dynamic pattern of behavior for various fault impedances.

5.6.3 Power system dynamic performance and its impacts

Power system’s stability has been recognized as an important problem for secure system operation. Generally, transient stability is the main concern on the majority of the power systems. As power systems have evolved through continuing growth, new operation technologies and controls in highly stressed conditions have emerged. More precisely, voltage stability and frequency stability have become greater concerns than in the past. A clear understanding of different types of stability and how they are interrelated is essential for the satisfactory design and operation of power systems.

![Fig.5.1 Categories of power system stabilities](image)

Power system stability is similar to the stability of any dynamic system, and has fundamental mathematical underpinnings. Precise definitions of stability can be found in the literature dealing with the rigorous mathematical theory of stability of dynamic systems. A circumstantial definition of Power System Dynamic Security and the corresponding types of Power System Stability is provided in [Kundur Prabha, et al. (2004)].

In Fig.5.1 concise classification of power system stability is provided. Additionally, another significant issue is the relationship between the concepts of power system reliability, security, and stability of a power system.
5.6.3.1 Power System Reliability: It refers to the probability of a required operation condition achievement, with few interruptions over an extended time period.

5.6.3.2 Power System Security: It refers to the risk assessment of system ability to survive disturbances (taking into account the probability of these contingencies) without any power supply interruption.

5.6.3.3 Power System Stability: It refers to the dynamic operation after a severe or moderate disturbance, consequently to an initial steady state operating condition. The analysis of security relates to the determination of the power system robustness to imminent disturbances. Assuming that a power system subjected to changes, it is important that when the changes are completed, the system settles to a new operating state where no technical constraints are violated.

This implies that, in addition to the next operating conditions being acceptable, the system should survive the transition to these conditions. The above characterization of system security clearly highlights two aspects of its analysis:

5.6.3.4 Static Security Analysis: It involves steady-state analysis of post-disturbance system conditions to verify that no voltage constraints are violated.

5.6.3.5 Dynamic Security Analysis: It involves examining different categories of system stability described in Section III. The general practice for dynamic security assessment has been to use a deterministic approach.

The power system is designed and operated to withstand a set of contingencies selected on the basis that they have a significant possibility of occurrence. In practice, they are usually defined as the loss of any single element in a power system either spontaneously or preceded by a single, double, or three phase fault.

This method is generally called as the N-1 criterion because it examines the behavior of an N-component network following the loss of any one of its components. In addition, emergency controls, such as generation tripping, load shedding, and controlled islanding, may be used to withstand such events and prevent widespread blackouts.

Ongoing power systems under deregulated energy markets with a diversity of participants, the deterministic approach may not be appropriate. There is a need to account for the probabilistic nature of system conditions and events, and to quantify and manage risk. The trend will be to expand the use of risk-based security assessment. In this approach, the probability of the system becoming unstable and its consequences are examined, and the degree of exposure to system failure is estimated. This approach is computationally intensive but is possible with today’s computing and analysis tools.
Case study:

**Wind pumps for irrigation**

Water pumping windmills for irrigation purposes, or wind pumps, are most economically competitive in areas that do not already have electricity for powering irrigation pumps. In these circumstances the alternatives are generally small engine driven pumps that are expensive to fuel and maintain. Low-lift applications for high value vegetable farming may be economically competitive in many parts of the world. The economic appeal of locally built windmills is even greater when the savings of scarce foreign exchange from reduced foreign imports and village level economic multiplier effects are considered. Other advantages of locally built windmills include the creation of village capital using local labor and materials, much lower initial cost, and avoidance of maintenance problems associated with engine-driven pumps. Such windmills appear to have more frequent but simpler maintenance requirements than manufactured windmills.

A small number of people are working on water pumping windmill designs in developing countries. The interesting contemporary examples of locally evolved designs include the Cretan sail windmills, the bamboo and cloth sail windmills of Thailand's salt ponds, and the locally built windmills of the Cape Verde Islands. All of these were built and maintained by local craftspeople. New designs of fabricated steel windmills that attempt to reduce costs have been built and tested in India, Sri Lanka, and elsewhere, for both water supply and irrigation applications.

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**Basic Components**

*Rotor/Fan:* Converts wind energy into rotary motion  
*Gear Box:* Converts rotary motion of fan into reciprocating motion  
*“Sucker Rod”:* Reciprocates to power underground pump  
*Pump:* With each motion of the sucker rod, draws water upwards through a one way check valve
**How It Works**

- Wind spins the bike wheel which moves the chain
- Turning the bottom chain ring and the shaft
- Pump goes up
- Check valves create suction that brings the water into the PVC
- Pump goes down, pushing water out the second check valve

**Advantages**

- Wind is essentially an unlimited resource
- Clean source of energy
- Facilitates storage of water
- Can double as an electric fence
- Low cost

**Disadvantages**

- Outdated Use of electric pumps delivering 20-30 gallons a minute hurt the windmill era
- Dependent on wind
- Small margin for error