INDIGENOUS DESIGN AND MANUFACTURING FOR ENERGY CRISIS SOLUTION: PROSPECTS FOR WIND POWER GENERATION SYSTEMS

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ABSTRACT: *With the ever increasing global demand of energy, wind power generation has seen a rapid growth in the new millennium. In the current energy crisis of Pakistan, wind energy is a promising option. This research paper covers the state-of-the art of the design features of modern power generation wind turbines in a comprehensive fashion, in addition to the other issues such as maintenance, safety, economics and environmental impacts. Following that, the prospects of modern wind power generation technology in Pakistan have been discussed with special emphasis on indigenization of this technology. Finally, suggestions for the indigenization policy framework have been delineated.*

Keywords: Indigenous design, Energy crisis solution, Wind turbine, Power generation system

INTRODUCTION

The power generation wind turbines, also termed as wind generators, are meant to convert the energy of wind into electricity. An effective design will be that which accomplishes this in an efficient and cost effective manner. The wind generators have been conventionally classified into two types, i.e., horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). For electric power generation, the horizontal axis wind turbines are more developed and are available in sizes of up to few megawatts. The vertical axis wind turbines, however, are not yet developed to megawatt scale power generation capacity and are typically used for off-grid small scale power generation. But research work is in progress to develop vertical axis wind turbines of large scale.

This research paper is an attempt to understand the design features of wind generators in an in-depth and comprehensive manner, so as to be able to benchmark the capabilities of the local industry to effectively and economically design and manufacture this class of energy generation systems. Sections 2 and 3 encompass the design features of horizontal- and vertical-axis wind turbines respectively; Section 4 covers the other important aspects; while the comparison of the two types of wind turbines is given in Section 5. Finally, a framework of the prospects of wind power generation technology in Pakistan has been suggested in Section 6, while conclusions have been drawn in Section 7.

DESIGN FEATURES OF HORIZONTAL AXIS POWER GENERATION WIND TURBINES

It reveals from the survey of current horizontal axis wind turbine models that the parts of such a wind turbine can be categorized into following sub-systems:

- Rotor
- Power Generation System
- Support Structures
- Regulation and Control Systems
- Accessories.

Rotor is that part of the turbine which interacts with the wind. It consists of a hub, incorporating the blades, mounted on the main shaft. Power generation system consists of a generator, usually with a gear transmission, followed by electric supply cables. The support structures include a base plate on which rotating components (shafts, generator and gear box) are mounted, a nacelle or turbine housing and a tower to support the machine. Control systems regulate a number of parameters like blade pitch control, yaw drive, braking system, and electric power generation controls. Accessories may include backup systems, etc.

Fig. 1 is a schematic diagram showing the major parts of a wind generator [1].

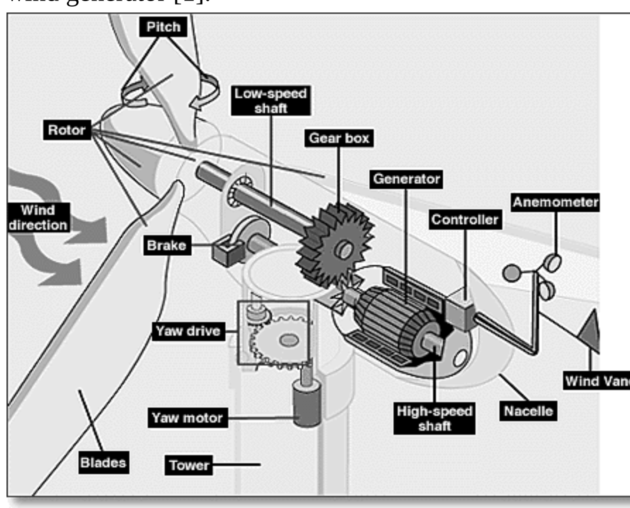


Fig. 1: Schematic of a Horizontal Axis Wind Turbine

Rotor

As stated, the rotor is that part of the wind turbine which deals with the wind to extract energy and is comprised of various design aspects.

Relation between Wind and Rotor

Wind is a diffused form of energy. It consists of a few components, among which only kinetic energy is useful for wind turbines. The maximum available power in wind is given by

$$P = \frac{1}{2}\rho \pi R^2 v^3 \qquad (1)$$

Where ρ represents the air density, R is swept area of the turbine rotor and v is wind speed [2]. Betz determined that the maximum amount of energy which can be extracted from a wind turbine is 59%. This is called Betz limit [3, 4].

Fig. 2 shows an idealized wind power characteristics curve [2]. The cut-in speed is that wind speed at which wind turbine starts generating power. Rated wind speed is the one at which turbine gives full output. A further increase in wind speed does not increase the turbine output, but after a certain limit, the wind speed may be so high that it can cause damage to the turbine. At such speed, called cut-out speed, turbine needs to be shut-down to prevent damage. Typical cut-in speeds range from 7 to 10 mph (3 to 4.5 m/s), rated speeds from 25 to 35 mph (11 to 15.5 m/s) and cut-out speeds are 45 mph (20 m/s) and above.

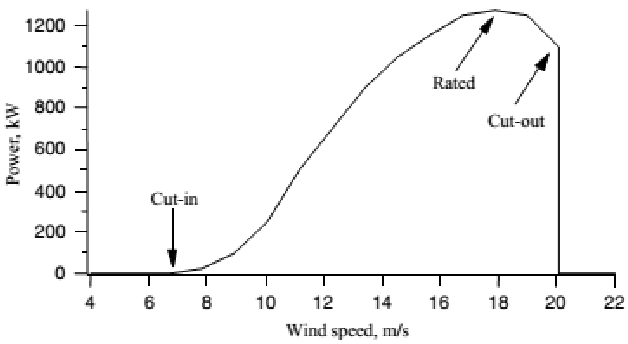


Fig. 2: Idealized Wind Power Characteristic Curve.

Wind Class

A wind class refers to the wind speed (mph or m/s) and associated wind power (W/m^2) at certain specific heights. For optimum design of a wind turbine, the site-specific knowledge of the wind class is required, the description of which is given in Table 1 [5].

Table 1: Description of Wind Classes

Class	98.4 ft (30 m) height			164 ft (50 m) height		
	Wind speed		Wind Power	Wind speed		Wind Power
	mph	m/s	W/m ^{2}	mph	m/s	W/m ^{2}
1	0-11.4	0-5.1	0-160	0-12.5	0-5.6	0-200
2	11.4-13.2	5.1-5.9	160-240	12.5-14.3	5.6-6.4	200-300
3	13.2-14.5	5.9-6.5	240-320	14.3-15.6	6.4-7.0	300-400
4	14.5-15.5	6.5-7.0	320-400	15.6-16.7	7.0-7.5	400-500
5	15.7-16.6	7.0-7.4	400-480	16.7-17.8	7.5-8.0	500-600
6	16.6-18.3	7.4-8.2	480-640	17.8-19.6	8.0-8.8	600-800
7	18.3-24.3	8.2-11.0	640-1600	19.6-26.5	8.8-11.9	800-2000

Working Principle

The horizontal axis wind turbines works on the principle of aerodynamic lift, resulting from the pressure difference of air while passing over the upper (longer) and lower (shorter) surface of blades made of airfoil shapes, causing them to rotate about the axis to which they are restrained. Drag, the second component of wind force, however, impedes this rotation. An efficient blade design will have a rather high lift-to-drag ratio. For optimum energy output at various wind speeds, this ratio can be changed along the length of the blade. Fig. 3 shows the schematic diagram of the working principle of a wind turbine [6].

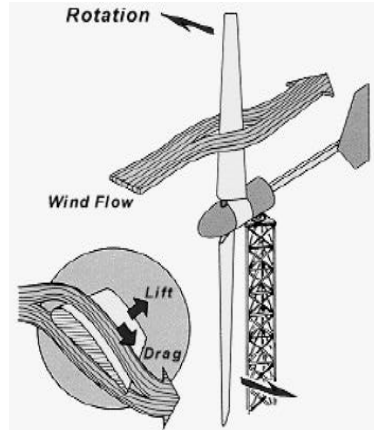


Fig. 3: Working Principle of a Horizontal Axis Wind Turbine - A Schematic Presentation

Rotor Design [2, 3, 4, 7, 8]

A wind turbine rotor consists of a hub onto which a suitable number of blades are attached. Fig. 4 illustrates some important concepts for any aerodynamic surface, including wind turbine blades. Part (a) of the figure shows the effect of wind on blade, part (b) shows some important angles related to turbine blade and part (c) shows the twisting of a blade.

Referring to figure (b), the apparent wind that touches the blade can be changed by the air. The rotational velocity that is created by the wind generated the drag and lift forces

The drag force are against the blade's movement but the lift force are in the direction of blade movement. Both the drag and lift forces push the blade, that reduces the wind speed. Lift and drag forces are described by the relations

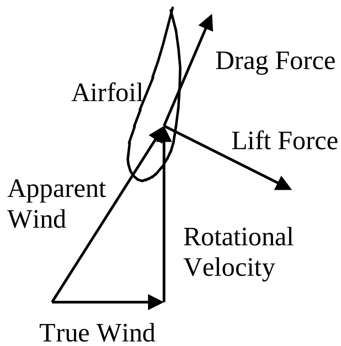
$$Lift = C_L \frac{\rho}{2} A V_a^2 \quad (2)$$

$$Drag = C_D \frac{\rho}{2} A V_a^2 \quad (3)$$

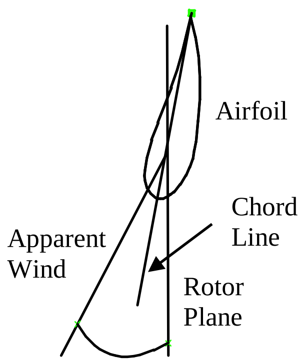
Where ρ represents the air density, A is the area of blade, V_a is the apparent wind speed and C_L and C_D are coefficients of lift and drag respectively. These coefficients depend on the cross section and shape of blade and the angle of attack, α, which is the angle between the apparent wind direction and the chord line of the airfoil. The chord line is a straight line which joins the leading and trailing edges. When designing a wind turbine rotor, the angle α depends on the angle of apparent wind ϕ and the blade angle β. So controlling over α provides the designer control over the lift and drag produced by the blade. For efficient performance, a section and angle of attack is selected to obtain a high lift to drag ratio. The highest lift/drag of majority of the blade sections typically corresponds $\alpha \approx 5^{\circ}$. The blade angle β thus can be found by the relation

$$\beta = \phi - 5 \quad (4)$$

With angles are shown in Fig. 4 (b)



(a) Effect of Wind on Blade



(b) Some Important Angles Related to Turbine Blade

(c) Twisting of a blade

Fig. 4: Illustrations of Blade Design

The rotational velocity of the blade is greater near its tip than that near its root, thus the angle ϕ is a function of span-wise location. This means that the ideal shape for the blade is twisted. This is shown in figure 4 (c). Also a blade does not have uniform chord width. Rather, it is narrowing towards the end.

Software tools are available which design turbine blades with given input parameters

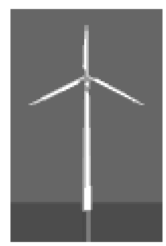
Number and Size of Blades

The optimum operation of a wind turbine is a function of certain parameters, among which number and size of blades is very important. The number of blades is determined on the basis of aerodynamic efficiency, component costs, system reliability and aesthetics [9]. Mostly, the HAWTs are being designed with three blade rotors in the upwind orientation, though two or more than three blade design is also possible.

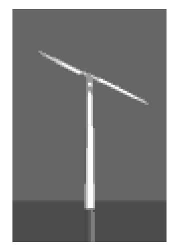
In three blade rotors, the tip speed ratios (blade-tip-speed/wind-speed) may reach up to 6 or 7. They have relatively low rotational inertia and are designed to spin at varying speeds, i.e., they can accelerate quickly as the wind speeds, keeping the tip speed ratio more nearly constant, hence having improved ability of energy capture. The symmetrically balanced design of three blades also helps maintain smooth yaw operation [9]. A 3-blade turbine is shown in Fig. 5 (a).

The 2-blade turbines, on the other hand, have the advantage of eliminating one blade and still capturing 97% of the energy captured by a 3-bladed wind turbine [10]. They rotate at higher speed, hence reducing the peak torque in the drive train, resulting in lower gear box and generator costs. But even number of blades gives stability problems for machines with stiff structures. The reason is that at the very moment a blade bends backwards, because it gets the maximum power from the wind, the opposite blade passes into the wind shade in front of the tower [11]. This uneven loading requires a more complex hub design with a hinged (teetering) rotor, i.e. the rotor has is able to tilt about a “teetered pin” in order to avoid heavy shocks to the turbine when a rotor blade passes the support tower. This arrangement may require additional shock absorbers to prevent the rotor blade from hitting the tower [11]. Fig. 5 (b) and (c) refer to a 2-blade turbine and teetering hub.

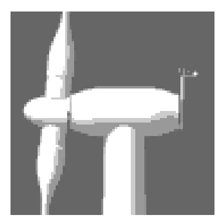
Single blade wind turbines are balanced by counterweights and have high rotational speed. This style has a greater imbalance of forces than a two bladed turbine and thus is not widely used. A single blade turbine is shown in Fig. 5 (d).



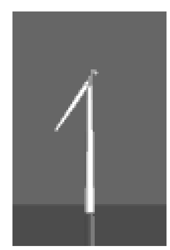
(a) 3-Blade Turbine



(b) 2-Blade Turbine



(c) Teetered Hub of 2-Blade Turbine



(d) 1-Blade Turbine

Figure 5: Illustrations of Number of Blades

The solidity of a rotor is defined as the percentage of the swept area actually occupied by the area of the blades. If a turbine has a large number of blades or very wide blades, it has a high solidity rotor, having low speed and high torque characteristics. Such a turbine is not able to withstand high loads developed at high wind speeds, making the operation un-safe. Hence not preferable for electric power generation.

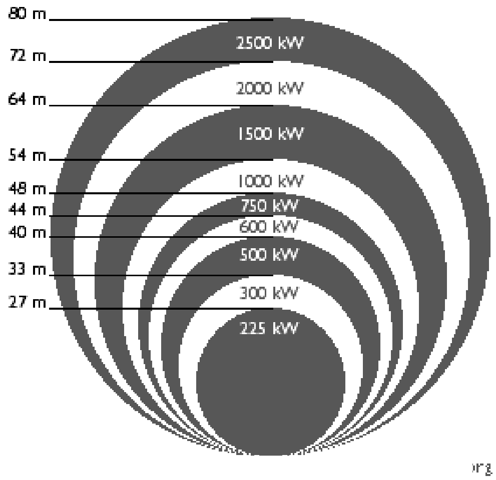


Fig. 6: Relationship Between Rotor Diameter and Power Output

Apart from number of blades, their size is also an important factor. Disc area of the rotor, alongwith the wind speed, determines the amount of energy which can be extracted from a turbine site. Fig. 6 shows the relationship between rotor diameter and power output [12]. Typical modern horizontal axis wind turbines have diameters between 40 and 90 meters and are rated between 500 kW and 2 MW.

POWER GENERATION SYSTEM

Power generation system of a horizontal axis wind turbine consists of a generator, drive shafts, power supply cables and electronic controls. The parts are mounted on a base plate and they reside inside the nacelle atop the tower. Arrangement of these parts can be well seen in Fig 1. Further details are as follows:

Drive Shafts with Gear Box

The power from the rotation of the wind turbine rotor is transferred to the generator through the power train, i.e., through the main shaft, the gear box and the high speed generator shaft. The main shaft can also be attached directly to the generator, but a very large generator would be required to account for the slow speed of the main shaft. A high speed low torque generator is typically much smaller in size and hence more useful considering the need to yaw the rotor in the wind. A gear drive, with a gear ratio of approximately 1:50, is usually applied between main shaft and generator shaft [13].

Wind Turbine Generators

In modern horizontal axis wind turbines, variable speed asynchronous generators are used most frequently. Generators of this type have properties which make them a suitable choice including reliability, low cost, variable speed and overload capacity.

A variable slip generator is typically used in a wind turbine. The amount of slip varies from 1% to 10% and can be used to adjust the rotor in gusting winds. At the rated output of the generator the slip is generally around 5%, which can be increased or decreased to account for small, rapid changes in wind speed.

The variable slip system has a faster response than the pitch control system. So the slip is used to account for the high frequency changes in speed, while the pitch control responds to lower frequency changes in speed.

Asynchronous generators require their stators to be magnetized before they work, which requires electric power. Thus a turbine with this type of generator should be either grid connected or use capacitors to provide this initial power.

To separately deal with low- and high-speed winds, using the combination of a small and a large generator is also an option. Similarly, pole changing generators are being increasingly used. Another design is 2-in-1 generator, capable to give two different outputs, for example, 200/1000 kW [14]. The multiple speed and power capacity generators have become more wide spreadly used throughout industry.

Grid Connection

The output of horizontal axis wind turbine generators is normal at 690 V, 3 phase, AC, which is then converted by transformers to 10-30 kV at 50-60 Hz for connection to the existing electrical grid. Electrical grid connection may either be direct or indirect. A direct grid connection requires a nearly constant turbine speed, where an indirect grid connection, the output is connected to a separate mini electronic AC-grid, which in turn is attached to the existing electrical power grid.

SUPPORT STRUCTURES

Support structures of a horizontal axis wind turbine include base plate, nacelle and towers, and vary in size based on the rotor and generator size.

Base Plate

Various parts of a horizontal axis wind turbine need to be supported and properly arranged by mounting them on a solid base plate. The base plate itself is attached on the tower and the yawing mechanism. Fig. 7 below is a simplified diagram showing a base plate with gear box and the generator mounted [15].

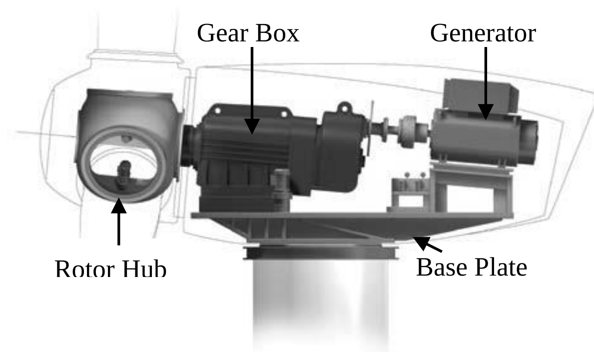


Fig. 7: Main Components Supported on Base Plate

Nacelle

The nacelle is the main housing of the wind turbine which accommodates all the components, except rotor, inside it, as shown in Fig. 8. It is usually made of fiberglass and allows for smooth air flow around the components.

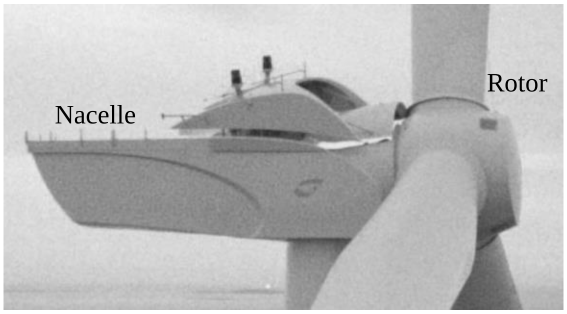


Fig. 8: Nacelle of a Wind Turbine

Towers

Towers hold the wind turbines at heights to take advantage of stronger winds. Wind speed and thus energy is lower near the ground due to surface roughness. It is also subject to variation at various parts of day and night due to solar heating. The wind speed and energy is not only higher away from the ground but also more uniform.

Common wind turbine towers are made of tubular steel, lattice, concrete or a guyed pole. Most large horizontal axis wind turbines have tubular steel towers, which are manufactured in 20-30 meters sections and bolted together on the site. The towers are conical to maintain strength and save materials. Lattice towers are manufactured from welded steel structural elements and the basic advantage is cost. Guyed pole towers are easy to install, but they are suitable for small turbines only and generally require a larger footprint on the ground. The three types of towers are shown in Fig. 9.

(a) Tubular Steel Tower (b) Lattice Tower (c) Guyed Pole Tower

Fig. 9: Types of Wind Turbine Towers

Though high towers help grasp more wind energy, the manufacturing and installation costs are higher. The price of a tower is generally around 20 percent of the total price of the turbine and therefore considerable to the final cost [16]. Careful calculations are therefore made to determine appropriate tower height by considering the related factors. Apart from the cost, terrain roughness, shape of the tower and additional income associated to height are important factors. A general observation is that a typical tower height is between two and three times the rotor radius.

Aerodynamic and structural dynamic issues are important to the tower design. High speed winds passing across the tower impart loads onto the tower, in addition to the forces created by the rotor.

WIND TURBINE CONTROL SYSTEMS

As the wind condition experienced by a wind turbine is not uniform, the turbine has to adapt to the wind conditions. This is achieved by electronic control of the blade pitch, shaft slip, etc. A description of electronic controllers and parameters controlled through them is given below.

Electronic Wind Turbine Controllers

A modern horizontal axis wind turbine incorporates up to three electronic controllers. The first is generally in the nacelle; another at the bottom of the tower and a third may be in the hub of the rotor. Data is shared between the various controllers, and in a wind farm data is shared between individual turbines as well as the external monitor and/or operator. Parameters that are continuously monitored include voltage, current, rotor speed, rotor direction, temperature, pressure, wind speed, vibration, etc. The controller operates the large number of devices such as switches, hydraulic pumps, valves and motors. The reliable operation of the controller(s) is necessary for sustained, proper working order of the turbine. Redundant systems are used as the fail-safe to minimize the down time of the turbine. Fig. 10 shows an electronic controller [17].

Fig. 10: An Electronic Wind Turbine Controller

Power Control Systems

When the wind speed exceeds beyond the cut-out speed, it damages to various components of the wind turbine. To avoid this situation, a power control system is required to limit the operation to safe conditions. Modern horizontal axis wind turbines employ one of the following power control systems [18].

Pitch Mechanism

In pitch controlled horizontal axis wind turbines, the rotor blades are able to turn around their longitudinal axis. Power output of the turbine is monitored by an electronic controller to maintain a nearly uniform output. At wind speeds above the cut-out speed, the power output can go above the rated value of the generator, potentially causing damage. The controller takes the power feedback and can pitch the rotor blades out of wind to reduce power output. Conversely, the blades are turned back into the wind when power output tends to drop. A successful pitch mechanism makes sure that the amount of pitch is that required to maintain rated power as much as possible. The mechanism is usually operated hydraulically with a spring loaded backup system to automatically pitch the blades out of wind in the event of a hydraulic failure.

Stall Mechanism

Stall controlled horizontal axis wind turbines use the rotor blades that are bolted onto the hub at a fixed angle. As the actual wind speed in the area increases to the point of onset of aerodynamic stall. As the speed increases, the stalled blade does not generate more force, thus acting as a passive speed control.

The advantage of the stall control is to remove the moving parts in the rotor and control system. Similarly, a stall control exemplifies a very complicated aerodynamic designs and the related problems, the major challenge is the stall-induced vibrations in the turbine. Another disadvantage of a fixed blade is the inability to adjust to varying wind conditions, as the wind speed changes so does the power output. Around two thirds of the wind turbines currently being installed in the world are stall controlled machines.

Active Stall Mechanism

Horizontal axis wind turbines with an active stall mechanism have pitch able blades in order to get the low wind speed and larger torque. As the turbine reaches its rated power, the blades are pitched such that the angle of attack of the rotor blades is increased making the blades go into a deeper stall, which limits the energy extracted from the wind. One of the advantages of an active stall is that power output is more accurately controlled than with passive stall. There is also an advantage that the turbine can run exactly the same rated power a wind turbine drop the electrical power output when it is used for higher wind speeds.

Yaw Mechanism

The horizontal axis wind turbine yaw mechanism turns the wind turbine's rotor into the wind to get the optimum use of wind. The yaw mechanism is generally driven by electric motors and gears. Fig. 11 shows a typical yaw mechanism of a turbine [19]. The gears from the yaw motors and the yaw brakes lie inside the bearing surface. The mechanism is activated by an electronic controller based on the wind direction indicator.

The wind turbine is said to have a yaw error if the rotor is not perpendicular to the wind, which implies that a less energy is extracted from the wind by the rotor. A higher bending torque is also experienced by the rotor when misaligned with the airflow.

Fig. 11: Yaw Mechanism of a Wind Turbine

Braking System

In electrically braking the wind turbine, the energy of the generator is dumped into a resistor bank that converts the kinetic energy of the turbine into the heat energy

This method is helpful when the load on the generator is suddenly decreased or cannot keep the turbine speed within its safe operational limit. When mechanical braking is used, a drum brake or disc brake holds the turbine at rest for maintenance. Such brakes are usually applied only after significantly slowing down the turbine speed.

Cable Twist Counter

Power supply cables run from generator through tower and can become twisted when the turbine is continuously yawed in the same direction. A cable twist counter records the number of turns and gives feedback to the controller to keep the cable untwisted by turning the turbine in opposite direction. The turbine is equipped with a pull switch as a backup arrangement, which is activated when the cable becomes too twisted.

Grid Connection and Power Quality

The term power quality is used to stabilize the frequency and voltage in the presence of the different forms of the electronic noise (e.g., flicker or harmonic distortion) which is then passed onto the existing electrical grid. Wind turbine output should have good power quality before it is connected to the grid. Below cut-in speed, electronic controls prevents turbine from being connecting to grid, avoiding a power transfer from the electrical grid to the turbine. Upon attaining the adequate speed, the generator is gradually connected to the grid through thyristors, which are electronically controlled semiconductor continuous switches.

DESIGN FEATURES OF VERTICAL AXIS POWER GENERATION WIND TURBINES

Like horizontal axis wind generators, parts of vertical axis wind generators can also be categorized into the following sub-systems:

- Rotor
- Power Generation System
- Support Structures
- Control Systems
- Accessories

Although these sub-systems serve the same purpose as in previous case, yet their design features are different, details of which are stated below:

Rotor

In a vertical axis wind turbine, the rotor consists of a vertical shaft on/around which blades are attached in a suitable number. Possible designs of blades include straight blades, curved blades, scoop blades and helical blades, etc. Before going through the design details, it is appropriate to understand the working principle of a vertical axis wind turbine.

Working Principle

Among the various types of blades of vertical axis wind turbines, only scoop type blades work with drag force of wind, while all the other types use lift force. The scoop type blades, as in conventional Savonius turbine, have high torque and low speed characteristics and not preferred for power generation.

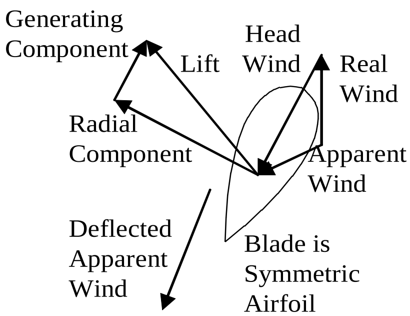


Fig. 12: Effect of Wind on the Blade of a Vertical Axis Wind Generator

Fig. 12 shows the effect of wind on the blade of a vertical axis wind generator [20]. It can be seen that one component of the lift vector contributes towards power generation. Also, the power generation takes place at almost all blade positions.

Blade/Rotor Design

As described earlier, the blades of different vertical axis wind turbine models are found to have of variety of shapes and designs. This is in contrast to horizontal axis wind turbines where straight blades are universally used.

Straight blade rotors are made by a number of manufacturers. Number and dimensions of blades, as well as, swept diameter of the rotor depend upon the design of the individual model. Many wind turbines consist of three-blade rotors. The others have rotors with 2, 4, 5, 12, 24, 44 blades. In case of large number of blades, the rotor may consist of more than one modules along the same vertical axis. For example, a twelve blade turbine consists of three modules with four blades in one module. Fig. 13 illustrates some designs of straight blade vertical axis wind turbines [21, 22].


(a) A 3-Blade 1-Module Rotor (b) A 24-Blade 1-Module Rotor

(c) A 12-Blade 3-Module Rotor

Fig. 13: Illustrations of Straight Blade Rotor Vertical Axis Wind Turbines

With straight blade rotor, turbines are available upto 75 kW output, but vigorous research is in progress to develop mega-watt size turbines.

Curved blades are the other well-known design. A rotor with curved blades looks like a large egg-beater, so it is also called egg-beater design. It is actually the improved form of the conventional Darrieus wind mill. Number and size of blades again depends upon the individual model. Current models are known to have blades from two to four. A rotor with four curved blades is shown in Fig. 14 [23]. Prototypes of upto 250 kW rated power have been developed in this design and further research is in progress.

Fig. 14: A Curved Blade Rotor with Four Blades

Helical blade design is a new development and getting increasingly popular. A number of manufacturers of vertical axis wind turbines have adopted this design. Number of blades in such models is found to be three. A helical blade wind turbine is shown in Fig. 15 below [24]. So far, maximum available size in this design is 5 kW.

Fig. 15: A Helical Blade Rotor with Three Blades

Apart from the commonly known designs, a couple of special designs are also observed. In one of the designs, the turbine comprises an L-shaped horizontal air intake and a parabolic air evacuation. This design is based on complex mathematical model. The maximum available size is 20 kW. The other design is known to be vertical axis involute spiral drag propulsion wind turbine. Currently, this design is at experimental stage. Fig. 16 shows the diagrams of both of the designs [25, 26].

(a) L-Shaped Horizontal Air Intake Parabolic Air Evacuation Wind Turbine (b) Vertical Axis Involute Spiral Drag Propulsion Wind Turbine

Fig. 16: Special Rotor Designs of Vertical Axis Wind Turbines

POWER GENERATION SYSTEM

One of the chief advantages of vertical axis wind generators is that none of the components needs to be mounted overhead with the rotor, as is required in a horizontal axis wind turbine. The electrical generator of a vertical axis wind turbine rests at ground level and couple, directly or indirectly, to the vertical shaft of the turbine. The small-size generators are permanent-magnet, multi-pole, synchronous generators, which supply single or three phase electricity from few watts to 50 kW. Larger generators are three phase induction generators, supplying electricity from 75-250 kW. No information could be available about the generation systems of under-construction mega-watt level vertical axis wind generators.

Usually the generator shaft is also in vertical position and directly coupled to the turbine shaft. But the shaft of a large-size generator can be horizontal and coupled to the turbine shaft through a gearing system.

Support Structures

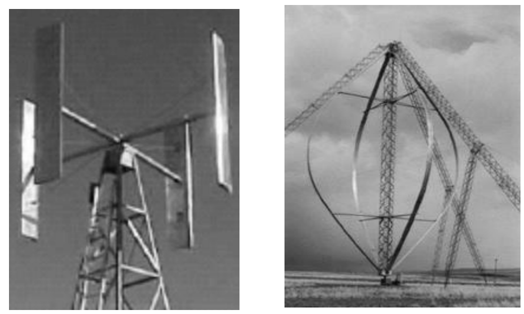
As evident, the support structures are required to hold the rotor and vertical shaft only, all the other parts being at ground level. Therefore, simpler and smaller supports work in this case. They get the further advantage of being able to operate at low cut-in speeds at lower altitudes. So the tower height of a vertical axis wind turbine is less than its horizontal axis counterpart.

An overview of the current models shows that small size turbines of this type are preferred to be roof-mounted. The rotor is attached at the upper portion of the shaft. Remaining portion of the shaft is supported in a tubular structure, which in turn is wall- or roof- mounted. Large size turbines are either tower-mounted or the vertical shaft is directly supported by guy-wires. Towers are of standard types i.e. stand-alone tubular towers or lattice towers. Illustrations are given in Fig. 17.

Control Systems

The control system of a wind turbine consists of electronic controllers, which, in response to a number of parameters continuously monitored, control the various functions. The parameters include voltage, current, rotor speed, temperature, pressure, wind speed and vibrations, etc., and are regularly shared among the controllers. Consequently, the controllers operate the various devices like switches, valves, motors and pumps to control the required functions.

(a) Roof-mounted Rotor (b) Tubular Tower



(c) Lattice Tower (d) Guy-Wire Support

Fig. 17: Support Structures of Vertical Axis Wind Turbines

The control functions of a vertical axis wind turbine are significantly less than those of horizontal axis wind turbines due to the obvious reasons. The design of a vertical axis turbine eliminates the need of any yaw mechanism or a cable twist counter. Many of the manufacturers use fixed blade rotor design, so not requiring a pitch control mechanism. Some of them even claim that their products have no need of over speed control systems.

However employing a cut-in speed control system and safety controls are inevitable. Most of the designs incorporate an automatically controlled braking system. Blade pitch mechanism is also employed in sophisticated designs.

The function of cut-in speed control system in vertical axis wind turbines is quite similar to that in horizontal axis wind turbines. The safety control system is employed to ensure the safe working of the wind turbine system. It takes the feedback of parameters like temperature, pressure and vibrations at certain points in the wind turbine system. If any of the parameters goes beyond permissible limits, the turbine is shut down through the safety control system.

The types of brakes in a typical automatic braking system may be mechanical, hydraulic, pneumatic or electrical resistance brakes. Most often, a suitable combination of various types is used instead of a single type.

In a blade pitch control mechanism, the straight blade is able to rotate about its axis. In order to take the full advantage of the wind power, blade angle is automatically adjusted according to the wind condition

Accessories

Power generation wind turbines are also used for off-grid applications in remote areas. Electrical storage devices are used to store the electrical energy in this case. One of the options is to use deep cycle, heavy duty, industrial type lead-acid batteries which are known for their reliability, long life, efficiency and affordable cost. Another option is to store the electrical energy into fuel cells. But this option requires further research work to be practical.

OTHER SIGNIFICANT ISSUES

Although this report focuses on design aspects of power generation wind turbines, there are certain other issues which need to be discussed due to their significance. They include maintenance, safety, economics and environmental impact, and are discussed below.

Maintenance of Wind Turbines

Different physical forces are considered on the turbines. The tip of rotor can rotate at the speed of 300 mph. Bearings that support the rotor or other moving parts are also subject to failure. The lifetime of these bearings depends on the loading conditions and level of maintenance provided.

Turbine manufacturers specify the required maintenance for specific wind turbine components. The entire wind system, including the tower, electrical storage devices and wiring should be inspected annually. Other routine maintenance might include changing the transmission oil, greasing the bearings and visual inspection of the blades, tower and electrical connections [27].

Safety Issues

The successful operation of a wind turbine system demands safety of both the machine and the people (operators and bystanders).

The intended life of a wind turbine is designed to be at least 20 years, i.e. 120,000 operation hours. Throughout its life, the wind turbine has to face adverse weather conditions. The machine is therefore equipped with suitable devices to ensure the safe function of the entire turbine. Sensors monitor vibrations, temperatures of the main components and certain other parameters. Devices that provide over speed protection to the turbine such as braking systems, use the feedback from sensors and protect from damage.

A number of measures are taken for the operator's safety, especially when they climb up the tower. One of the reasons of preferring tubular towers over lattice towers is that they are more safe and comfortable for workers. The workers are equipped with parachutist-like safety harness for their protection in case of an accidental fall. Protection from the machinery, fire protection and electrical insulation protection are also mandatory.

Economic Issues

A wind energy system requires a large initial capital investment, but over its lifetime it will provide years of energy with no fuel cost while the costs of other sources of energy may escalate. Installation cost per kWh of power generation is higher for small systems compared to a large ones, the lowest cost being corresponding to multiple units installed at one location. Off-grid remote systems cost even more.

Payback period of wind turbine system is typically about 20 years. Another factor into the payback period is the amount of excess power to be sold to the utility company. So cost savings from wind energy can be more significant further reducing the payback period.

In order to promote alternate energy resources, some donor agencies provide loans of up to $250,000 at 0% interest for 20 years [27].

Environmental Issues

Environmental issues of wind turbine systems include noise and effect on wild life. Wind turbines with their high towers and long blades are currently located in open areas with consistent winds. Generally, they are installed in large numbers to make a "wind farm".

Like any other machine, which interacts with air, a wind turbine makes noise. But appropriate design of blades, along with fine surface finish, reduce the noise to an acceptable level. As other rotating parts are well designed and well balanced, they do not make a noise.

As far as impact on wild life is concerned, careful studies are conducted for this purpose at each site. The major danger to the environment is to birds. It has been found that birds have natural tendency of changing their direction before being struck a wind turbine blades, thus not facing any serious danger. Statistical studies show a very small number of bird fatalities due to wind turbine strikes.

COMPARISON OF HORIZONTAL-AXIS AND VERTICAL-AXIS WIND GENERATORS

The comparison of the two types of wind generators can be made under the following headings:

Power Generation

The horizontal axis wind generators have propeller type rotors with twisted blades. Twisting of the blades gives accurate angle of attack and hence efficient conversion of wind energy into electricity. As they are available in megawatt capacities, they are suitable for large scale production.

In case of vertical axis wind generators, the efficiency of conversion of wind energy to electricity is considerably less. Turbines of this type are not yet available in large capacity, so not able to contribute in large scale power generation.

Design Complexity

Design of horizontal axis wind turbines is much more complex than their vertical axis counterparts. In the former case, high altitude and high strength tower is required to support the complete assembly in speedy wind at desired height. The number of functions controlled by the control system is considerably large in this case. The latter case refers to simpler and smaller structures, along with less number of functions to control.

Site Location

The horizontal axis wind turbines are not considered to be suitable for urban use. They produce noise, can be hazardous to any type of flying objects and may throw chunks of ice in chilled environments. The vertical axis ones are very quiet in operation, cause no hazard to flying objects and safe in icy environments. Being a suitable choice for urban use, they can be mounted atop the residential buildings even.

Future Aspects

Traditionally, the horizontal axis wind turbines have been considered to be more suitable choice for power generation due to their reliability and efficiency. As mentioned earlier, their twisted blades help efficient conversion of wind energy to electricity. They are considered to be reliable due to their low torque characteristics, easy to stop pitch able blades and the fact that blades are to the side of the turbine's center of gravity which helps stability. As a result, vibrations and fatigue in the system remains within permissible limits. At the other side, the high torque characteristics of a conventional vertical axis wind turbine were found to generate too much thrust on the transmission and structure, ultimately leading to fatigue failure.

As the HAWTs have rapidly developed up the capacity of few megawatts, their very large sizes have associated problems. Though the non-metallic blades are lighter in weight and undergo less metal fatigue, they are still very heavy and also subject to bending due to wind force. Controlling the fatigue in blades and other parts of the turbine is a significant issue in the current large size models. Steven Peace states, [28].

The vertical axis wind generators could not be significantly developed due to the above mentioned reasons. But their simple, noiseless, rugged and reliable design is again drawing attention. Efforts remained successful to remove their traditional faults by employing modern tools of aerodynamics and structural dynamics. A number of companies in North America and Europe are currently producing small and medium capacity vertical axis wind generators. Hectic research efforts are in progress to develop wind generators of this type with capacity of one megawatt or more.

PROSPECTS IN PAKISTAN

Pakistan is the sixth most populous country of the world with ever-increasing demand of energy. In summers, the short-fall of energy reaches up to 7000 MW. This is one of the major hurdles in economic growth of the country since more than a decade now. Among the various types of conventional and renewable energy resources, wind energy has seen the highest growth worldwide in the new millennium. The top five producers generated more than 200,000 MW in 2012, as compared to only 18,000 MW in 2001 [29]. Owing to the renewable and environment–friendly nature of this form of energy, it is very important to consider it to meet the energy demand of the country.

The prospects of wind power generation technology in Pakistan can be viewed under the following sub-headings.

Potential Sites

The potential wind energy sites of Pakistan are shown in Fig. 18 [30]. About 3% of the land area has Class 4+ winds, good-to-excellent for power generation, with a total potential of 132,000 MW. This potential is a huge and precious natural resource. If Class 3 winds are also included, the wind area comes out to be 9% of the total. But Class 3 winds are suitable only for small off-grid applications.

One of the major wind energy regions spans from Karachi to Hyderabad. The second one consists of the hilly and semi-hilly areas ranging from Kallar Kahar to beyond Mardan, including Islamabad, also covering some part of Kashmir. The potential wind-energy sites in Baluchistan are excellent but scattered faraway in the areas of Nokkundi, Chagai, Makran and Quetta, etc.

The horizontal-axis wind generators are typically large-scale grid-connected systems installed in open sites. Their vertical-axis counterparts are small-scale off-grid systems, primarily suitable for roof tops. The viability/selection of the right type of system depends not only upon the wind class available but also on the population density based power needs in that region. Hence, the area from Karachi to Hyderabad is ideal for both small- and large-scale wind power generation owing to three factors, i.e., availability of good to excellent class of wind, high energy demand due to high population density in the region and presence of high rise buildings to mount the roof-top modules. The same parameters exist in the hilly region around Islamabad. The energy sites in Baluchistan are more suitable for large-scale power generation. However, high transmission-line losses are anticipated due to long **distances.**

Government Incentives

According to Alternative Energy Development Board (AEDB) [34], government of Pakistan has offered a number of incentives to increase the wind power generation in the country, such as, guaranteed electricity purchase at attractive tariff, exemption on duties and taxes, and protection against risks, etc. Consequently, 21 wind generation projects are grid-connected and a number of them are in progress.

Indigenous Development of Technology

Although AEDB [31] recognizes the indigenous development of wind power generation technology as one of the potential areas for the promotion of wind power generation in the country, no tangible plan/framework could be found in this regard

The indigenous development of wind power generation systems needs to be seen with the analogy of indigenous development of auto parts manufacturing industry of the country [32-34]. The local vendors entered the auto parts manufacturing in 1985 through Industry Specific Deletion Programs (ISDPs) and Product Specific Deletion Program (PSDP). Having passed through the Preparation Phase from 1985 to 2005, this sector is now in the development phase, involved in the production of a number of types of vehicles with parts deletion from 70% to over 90%. This sector is the second largest tax payer of the country, contributing around 6% of the GDP, providing direct employment to around 400,000 workers and indirect employment to over 3 million people.

In the light of the detailed considerations of Sections 2 and 3, features of a policy framework for indigenization of wind power generation technology are suggested herein.

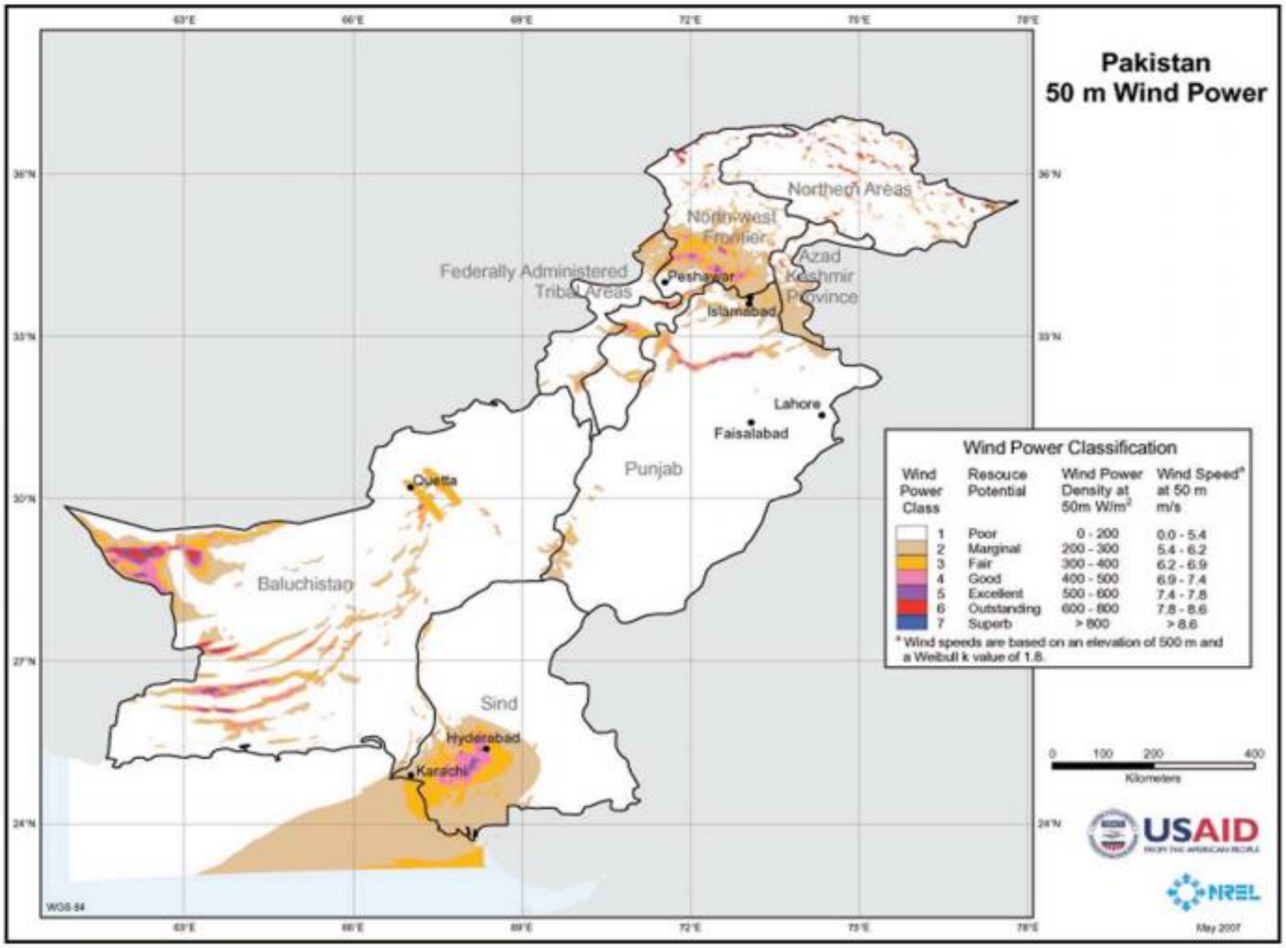


Fig. 18: Pakistan's Wind Resources Major Areas

- The rotor is considered to be the most important part of a wind generator. The turbine blades are made of high-strength and light-weight materials such as glass- and carbon-fiber reinforced polymer composite materials or aluminum alloys; glass-fiber reinforcement being the most common type.
- The design of wind turbine blades is very critical as they are subject to fatigue which may lead to failure. Especially, in large diameter rotors, the blade-tip velocity may reach the sonic velocity. Design indigenization of this hi-tech part can be brought about with the expertise of engineering research organizations using enough contemporary research material available and finite element analysis tools. The suitability of the fatigue test equipment at various engineering organizations needs to be checked for small and medium size blades. However, there is little chance of availability of such type of equipment for large blades.
- One of the benefits of fiber reinforced polymer composite materials is their ease of manufacture. The local fiberglass manufacturers are involved in making parts as big as boat hulls, mostly with hand lay-up technique. Their existing technology can be utilized/upgraded to manufacture turbine blades.
- The variable speed asynchronous generators are typically used in horizontal-axis wind turbines, while synchronous generators and three phase induction generators are used in vertical-axis wind turbines. The local electric-generator manufacturers are making stationary speed generators coupled with a suitable type of thermodynamic system. The technology of these manufacturers should be evaluated to make the generators of desired specifications and power rating. Alternatively, if economically viable, imported generators may also be used.
- The support structures of horizontal-axis wind turbines consist of base plate, nacelle and towers. Those of vertical-axis wind turbines consist simply of towers. As these parts are subjected to dynamic loading, their design analysis is of prime importance. The expertise of the engineering research organizations can be helpful in the same way as that for turbine blade analysis.
- Manufacturing of the towers can be done in large scale engineering works. An alternate option is modify the design of transmission towers to support a wind turbine structure.
- The nacelle and the base-plate manufacturing are the purview of the local foundry industry, seemingly to have enough existing capability to deal with this kind of work.
- The power control systems, consisting mainly of pitch, stall and yaw mechanisms and braking systems, are feed-back controlled mechanical systems. The mechanical systems of this type can be designed and manufactured by local auto-parts manufacturers, specifically the ones dealing with heavy duty gear transmission systems. The feedback control

systems can be designed and installed by the industrial automation companies. The wind turbine controllers for data monitoring and controlling the different types of devices can also be dealt with by the same types of companies.

CONCLUSIONS

The above-stated considerations can be summed-up to yield the following conclusions:

1. As wind energy generation is rapidly growing worldwide, it is economically and technically a viable solution of the power shortfall of the country.
2. The 132 terawatt wind power capacity of the mainland is a precious natural source, though the huge off-shore wind power potential is still unexplored.
3. Although the national wind data is available, a one year site specific data is necessary before the actual installation of a wind generator. It is suggested that data collection arrangements should be made at the promising sites around the population hubs of Karachi to Hyderabad, Islamabad to Mardan and Quetta.
4. In these areas, the use of multi-story buildings for mounting the roof-top wind generators should be encouraged. Existing building designs should be evaluated from this angle. More importantly, the new building structures should be designed to withstand the loads of wind generators.
5. The economic incentives offered by the government are attractive for the investors.
6. Indigenization of wind power generation technology in fact is the need of this time and achievable with the analogy of indigenization of auto parts manufacturers through Industry Specific Deletion Programs (ISDPs) and Product Specific Deletion Program (PSDP). The main players of the suggested program are engineering research organizations, companies dealing with engineering services and engineering works, manufacturers of fiberglass products, auto parts and generators manufacturers and industrial automation companies. It is anticipated that the existing technology of many of them will be adequate to achieve the targets. Where technological gaps exist, they will be bridgeable with appropriate planning and resource allocation.

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