The Evolution of Wind Power Technology—a Review

Shikha, *Non-member*
Dr T S Bhatt, *Non-member*
Prof D P Kothari, *Fellow*

Though a comparatively new industry, wind power development has reached a level of maturity, which could be taken upon for further innovation and growth in meeting the future energy needs in much greater proportion. Remarkable advances in wind power design have been achieved due to modern technological developments. New aerodynamic controls, such as, ailerons are being developed, that are cheap and yet more reliable. Current research techniques are producing stronger, lighter and more efficient blades for the turbines. Computer-controlled wind plants give optimum power output from available winds. These developments and growing trends towards wind energy can signal a promising future for the wind energy industries. The paper reviews the global development of wind energy, development of the technology of wind turbines and the various parameters related to wind energy conversion (selection of site, generators, drive systems, aerofoils, blade profile, etc). The different existing and new control devices for wind energy systems have been discussed. The paper also reviews the ongoing and future technological developments and the growing power of computers in wind energy conversion systems (WECS) in the past few years.

Keywords : Wind power; Wind turbine technology; Wind energy conversion; Wind electric generator

INTRODUCTION

Although, wind energy meets only a small amount of the world's energy needs today, a recent report of environment pressure group, Greenpeace states that about 10% of the electricity requirement can be supplied by wind[1] by the year 2020. With wind plant availability often reaching 95%, wind power has proven itself to be a realistic energy supply alternative[2]. Electric power produced by WECS is undergoing extensive research and revitalization as a viable solution to clean air power generation[3]. Today it is generally accepted and proved, that wind is far ahead of all other 'solar based' technologies, next to large-scale hydro power, regarding unit cost (kWh-price) and operational reliability. At good windy sites, it is already totally competitive with that of traditional fossil fuel generation technologies-even with coal based generation[4,5]. With its improved technology and superior economics, experts predict wind power could capture 5% of the world energy market[6] by the year 2020.

GLOBAL DEVELOPMENTS

The current global installed capacity of wind power is around 16 GW, with 2.5 GW installed in the year 2000 alone. In rupee terms the installed capacity is worth over Rs 55700 crore. Of the total installation capacity in the world, Germany, the US, Denmark and Spain account for over 80%. Europe accounts for the bulk of this capacity at 9737 MW followed by North America 2619 MW, Asia 1376 MW, Pacific Region 116 MW, South and Central America 87 MW, and Middle East and Africa 39 MW.

Wind power has entered the new millennium with a lion's roar. The wind energy capacity around the world has grown from under 2000 MW in 1990 to around 16000 MW at the end of 2000. Growth in the past three years has been led by Germany, the US, Spain, Denmark and India. In 1999, the annual installation of wind power capacity increased by 51%. Approximately 81% of the new capacity was installed in Europe. In the recent years wind power industry recorded over 40% growth. Germany is the industry leader with 4445 MW operating capacity. US has an installed capacity of 2500 MW. After Germany and US, the world's main wind energy producers are Denmark at 1742 MW, Spain at 1530 MW and India at 1059 MW.

In Europe, Germany, Spain and Denmark lead the others. The Netherlands has an installed capacity of 433 MW, the UK 362 MW, Italy 277 MW, Sweden 220 MW, Greece 87 MW and Ireland 73 MW. The rest of the European countries have less than 100 MW. In America, US leads as stated above. Canada has an installed capacity of 127 MW, Mexico 2 MW and the rest of America 94 MW. In Asia, India is far ahead of its neighbours, China comes next with 262 MW, Japan 68 MW and the others 11 MW. The rest of the world has a total installed capacity of 151 MW. Of this Australia and New Zealand account for 45 MW, Pacific Islands 5 MW, North Africa 64 MW, West Asia 18 MW and former Soviet Union 19 MW[7,8].

WIND ENERGY CONVERSION

There are three basic ways in which wind can be captured to turn a shaft : axial, diametral and tangential flow. The horizontal axis wind turbine (HAWT) uses the axial flow method in which the axis of rotation is horizontal. The vertical axis wind turbine (VAWT) uses the diametral flow in which the axis of rotation is vertical. Both designs convert the kinetic energy of the wind to produce electricity[9]. The rotational energy produced by the rotation of blades can be used to operate a mechanical device, such as a water pump, or to produce electricity by means of a generator[2].

Shikha, Dr T S Bhatti and Prof D P Kothari are with Central for Energy Studies, IIT, Delhi, Hauz Khas, New Delhi 110 016.

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While wind energy conversion is relatively simple in concept, turbine design can be quite complex due to drag forces between the blades. According to Thomas and Urquhart, at present, both the HAWT and VAWT designs are very efficient, however both are being rigorously tested and improved[3]. Two likely configurations for advanced HAWT designs were first suggested in a configuration study by Swift, *et al*[10]. In future, the hypothesized VAWT will almost certainly retain one aspect of its current strength : simplicity. As suggested by Dodd, the key to future success with this configuration, will be cost effective manufacturing techniques that will produce significantly less expensive blades, based on cost per unit length[11].

The wind turbine technology has a unique technical identity and unique demands in terms of the methods used for design[12]. The behaviour of a modern wind turbine is made up of a complex interaction of components and subsystems and its design requires the skills of a multidisciplinary team of engineers with expertise in diverse areas : atmospheric wind flow, rotor aerodynamics, control, mechanical systems, electrical systems and civil engineering. Quarton studied the design problem, which is particularly complicated since wind turbines have little respect for engineering conventions[13]. Modern wind turbines are based on the principle of aerodynamics and are designed to deliver energy across a range of wind speeds and at lower costs. This technology improves wind capture, reduces stresses and lengthens turbine life[1]. Some of the important parameters that need to be taken care of are as mentioned.

Selection of Site

Most wind resources, even favourable ones, have not been used up to now, the main reason being the lack of the expertise, concerning both methods of site selection and technical aspects of wind power, that is essential for defining wind projects and planning wind farms[14]. The wind constantly changes in direction and speed and is also affected by altitude, temperature and terrain. The wind speed if doubled can give eight times more power available to the rotor. Consequently, the site location of the wind turbine is of paramount concern, as recommended by Hunt[15]. The following factors should be considered in selection of site for wind power plants :

- A site should have a high annual average velocity, optimum mean velocity of 18 km/hr and the mean deviations of wind velocities should be minimum.
- It is always preferable to install wind-mills at sea shore, as the direction of the wind is in a particular direction and it has tremendous impact on the rotation of blades.
- There should not be any obstructions to avoid any infringement in flow of wind and allied to this more number of units can be installed in rows and columns to trap wind energy efficiently.
- The top of the smooth shaped hills with all around exposure provides mean speeds of 35% to 50% above low lands and also offers advantage of creating higher mean speeds.
- The best places are where vortex is formed by hills and valleys resulting in high wind speeds. This is also called a funneling effect, which can be intensified by contour shaping of hills.
- Cost of land should be reasonable and bearing capacity should be high[16].

Although, wind power may prove practical for small power needs in isolated sites, for maximum flexibility, it should be used in conjunction with other methods of power generation to ensure continuity as suggested by Nagrath and Kothari[17].

Airfoils

The development of special-purpose airfoils for HAWTs began in 1984 as a joint effort between the National Renewable Energy Laboratory (NREL), and Airfoils, Incorporated. Prior to that time, turbine blade designers used airfoils developed for aircraft wings. Since 1984, seven airfoil families have been developed. NREL airfoil families are used on replacement blades and wind turbines developed by Atlantic Orient Corporation, Advanced Wind Turbines, and Zond Systems. Annual energy improvements from the NREL airfoil families as projected by Thresher, *et al* are to be 23% to 30% for stall-regulated turbines, 8% to 20% for variable-pitch turbines, and 8% to 10% for variable-speed turbines[18].

Number of Blades

The number of blades is always a big issue : one-bladed rotors minimize energy loss from drag forces, but two-bladed and three-bladed rotors are considered the best trade-off for stability, aerodynamic performance and cost[3]. The associated energy penalty for a one-bladed rotor compared with a three-bladed rotor is about 10%, and for a two-bladed rotor compared with three about 4 %. The single-bladed rotor requires to be hinged with a counter balance and is not lighter than a two-bladed rotor. The two-bladed rotor, although in better shape dynamically than a single-bladed rotor, must accept very high cyclic loading if a rigid rotor hub system is employed or provide a so called teeter bearing to allow the rotor blade to rock (as a pair) to alleviate blade, drive train and tower head loading. The three-bladed rotor is simpler dynamically and a little more efficient aerodynamically. If one, two or three-bladed rotors are designed for similar tip speeds, then the rotor blades of the three-bladed rotor are more highly stressed than for two or one-bladed system and thus rotor blade costs will be higher for the three-bladed system. Of course it is the overall effect on the wind turbine cost effectiveness (energy capture / capital cost) that really matters and that is only determined with a view of the complete design. Determination of the optimum design configurations has been researched in depth in studies supported by European Commission[19].

Blade Profile

The early airfoils based on readily available data from aircraft industry exhibited low lift-to-drag ratio with moderate power coefficients of the rotor. Modern blades evolved to its present shape through specific design efforts for meeting the requirement of wind turbine applications have now higher lift-to-drag ratio and power coefficient of around 0.5, an increase by about 20 %. The blades are built thicker, specially at the root where the bending loads are very high. Special considerations are also taken in the design to encounter induced vibration which had been the cause of many instances of fatigue failure under unsteady wind conditions. Construction of very large turbines however continues to be a challenging task because of possible occurrence of vibrations over a wide range. Glass fibre with reinforced polyester and foam (to reduce buckling danger) is the common construction material for wind turbine blades. This structure is better adopted to the typical loads on the after body of the blade. New construction materials like wood epoxy, carbon fibre etc. can be better adopted for typical loads on the blade, as recommended by Dutta, *et al*[20]. The low energy density of wind and its availability, which varies from moment to moment necessitates a relatively large capture unit. Increasing the diameter of the rotor disc (by increasing the blade length) will allow the WECs to intercept more wind and, thereby, harnesss more power. However, the choice of the WECs to intercept more wind and, thereby harness more power. However, the choice of the WECs size, as suggested by Hunt, should not be made solely on this basis but in conjunction with the specifications and design limitations provided by the manufacturer[15].

Wind Electric Generator (WEG) and Drive Systems

Fluctuating winds have an unpredictable effect on the wind turbine. If this fluctuating wind is used to rotate the turbine, which in turn rotates the generator, there is definite variation of the frequency, voltage and power which is undesirable. The variation of frequency and voltage definitely affect system loads.

Selection of Generator

Generally ac generator (alternator) is used to generate electric power in wind mills, but the output voltage and frequency of the alternator depends on the speed of the rotor which is variable, so it requires very frequent regulation of speed without which there is a possibility of loss of synchronism. In order to overcome such problems, an induction generator can be employed instead of an alternator for variable speed operation. Induction generator is excited from already existing grid system which has certain frequency and voltage, therefore the induction generator gets connected parallel with the grid system, inspite of variations in wind velocity[21]. The main advantage of this generator lies in the fact that it reduces the 'short circuit risk' of the power station. Its construction is simple and rugged and the cost is one-tenth of the synchronous generator. Although, the induction machines always operate at lagging power factor and this is a major weakness, as studied by Ooi and David[22], but this generator does not need to be driven continuously at fixed speed. This is the prime reason for its usage in wind power generation. Synchronization is not required and further as a bonus there is no hunting problem[23].

Drive Systems

Operation of WEG at two different speeds by using two-winding generators is a usual practice. This allows lower rotational speed at low wind for optimum energy capture with increased efficiency. Variable-speed mode of operation has come up as a useful alternative specially for larger WEGs. In principle, this arrangement is superior to the conventional system in terms of efficiency of energy capture besides ensuring grid quality power. Major benefits of this system are

- Improved energy capture in low wind.
- Control of output power factor.
- Reduced drive train torque.

Under this general arrangement, following options are available :

- Wide range variable-speed operation, where drive has speed range of 2.5 or 3 to 1.
- Limited range variable-speed operation, with speed range of about 1.5 or 2 to 1.
- Narrow band variable-speed operation, with speed range[24, 25] of 1.1. to 1
- Direct-drive system, in which the speed-increasing gear-box is eliminated and the generator can operate at the rotational speed of the rotor.

Dutta, *et al* concluded that, while it would appear optimistic to explore significant material or cost saving in large wind turbines solely through the introduction of a direct-drive system, it is likely that in a fully integrated design providing simple design, besides provision of wide range variable-speed and elimination of gear-box, maintenance would favour the continuing development of direct-drive system[20].

CONTROL SYSTEM

Control of WEG

The controller is provided with display unit for display of instantaneous position of generation, active and reactive consumption, rotor rpm and generator rpm, generator temperature, different grid parameters etc. It also has data storage capacity and memory to keep records of different faults. The data pertaining to power curve can also be stored.

The controller has the facility to communicate and interact with remotely located control system and other computers for data feeding and analysis. Normally some hundred set points are available within the controller for tuning as per the operating conditions during commissioning. Further sophistication has been added in some of the WEGs recently developed for a remote and off-shore location where the number of parameters are exceeding 500. These are used for adjusting to the changing conditions automatically and totally eliminating all hand setting exercises which are difficult at such locations[20].

Remote Monitoring and Control

For large size wind farms, provision of Central Monitoring and Control System (CMCS) has become almost an integral feature. This is despite the fact that the WEGs are individually equipped with monitoring the operating conditions and function for indication and control. In this system, the parameters monitored by each controller including WEG fault condition are repeated at the control unit, with added facility for individual and group switching. Under the computer-based supervisory control and data acquisition (SCADA) system, the operator could also modify the operating characteristics of the connected WEGs from a remote central location[20].

Stall and Pitch Regulation

Stall regulation solely depends upon the inherent characteristic of airflow over the blade contour to effect power control on the wind turbine at very high wind speed. While this provides a robust means for wind power control, pitch control by its additional feathering action has the following distinct advantages :

- Easy start-up by wind;
- More capture of wind power; and
- Assist aerodynamic brake action enhancing life of brakes.

Adopted by some of the major manufacturers, pitch regulation however calls for some complex mechanism with increased maintenance problem compared to stall control. Walker and Jenkins studied that, under active stall technique, the turbine blades, which are normally left at fixed position could change their pitch angle during braking[21].

Use of Power Electronics

Gardner stated that, variable-speed mode of operation depends upon power electronics for running of generators at varying speed, made possible by frequency changes for connecting to a fixed frequency network[24]. New technology has been developed which uses power electronics to allow variable-rotor-speed operation to improve efficiency, control structural loads and improve power quality,. Lucas, *et al* studied the literature in detail and estimated that variable-speed operation can increase energy capture by up to 15%, which is about the same level as the increase in cost[26].

A traditional advantage of direct-drive generators with external excitation was that the strength of the field current served as an additional output control variable. The latest developments in power electronics have removed this output control disadvantage for permanent magnet generator (PMG). With the new technology, generator current can be electronically 'blocked' to influence generator torque[27].

Aerodynamic Control Devices

Aerodynamic control devices provide two benefits : they are used for over-speed control and power modulation. Incorporated into turbine blades, aerodynamic control devices (also called trailing edge devices) can adjust the rotor aerodynamic driving forces and thus optimize energy capture, control loads and control rotor speed. These aerodynamic controls are often compared to the ailerons used on aircraft. Various trailing-edge control devices have been incorporated in wind turbines that are in development or commercially available. Tangler and Somers studied these trailing edge control devices as they are thought to offer some cost and control advantages over pitch control and tip controls, which are typically used on existing designs, although these advantages are yet to be proven[28].

THE INCREASING POWER OF COMPUTERS

The sophistication of the analytical methods used as the basis of wind turbine design has increased enormously over the last 20 years. As control systems have become more complicated, particularly with the advent of variable-speed operation, the procedures adopted for the design and commissioning of control algorithms have to be improved considerably. In contrast with the early days of the industry when controllers were scarcely designed but rather 'tuned' by the commissioning engineer in the field, the design of a modern wind turbine control system now routinely involves a great-deal of computer-based analysis[13].

Mathematical Models

Through the use of knowledge gained from fundamental research, domonstration projects and measurement programs, research workers have been able to develop and validate mathematical models, which provide more reliable representations of both wind turbine behaviour and wind input. Validation of the mathematical models has been and clearly remains a crucial aspect of the wind turbine research program and has depended on the availability of high quality measurements. A particularly important European Union (EU) funded research project in this context was the 'wind turbine benchmark exercise on mechanical loads', by Grol[29], completed in 1991. This project, which involved the collaboration of organisations from several European countries, enabled the first coordinated investigation of the maturity and reliability of contemporary wind turbine computer models[13].

Computer-based Analysis

Beginning with simple calculations based largely on engineering intuition, the approach to wind turbine design has been transformed to the point where sophisticated computer-based analysis is now performed routinely throughout the industry[13].

A modern WEG depends upon computer for its operation and covers right from its normal start-up to generation till such time when wind falls or grid is disconnected or the WEG becomes faulty[20]. Computer processing power and available memory have increased at a phenomenal rate over the 20 years that the modern wind turbine industry has been in existence. Using standard desktop PC hardware, it is now possible for a designer to make use of calculation methods and design software that would have been impossible using the computer hardware generally available in the early 1980's. The increased power and memory of computers, coupled with the possiblities for extermely user-friendly software environments, allow the wind turbine designer to undertake sophisticated design calculations in a straightforward and convenient manner[13].

From Research Codes to Design Tools

Although the wind turbine or wind farm designer clearly requires reliable, well-validated calculation methods based on the sophisticated models developed by research organisations, he also has a number of other important requirements. For use as a design tool, rather than a research code, a computer program must have the following features :

- User-friendly with convenient pre-processing and post-processing of data;
- Capable of rapid design calculations on standard computer hardware;
- Produces results of direct use for design and certification; and
- Well documented.

It is a challenge to the research community who have been responsible for developing reliable wind turbine mathematical models that they should now develop software tools which meet these requirements and which are therefore suitable for use by designers. This process is well under way and there are already a number of commercially available computer programs, which have progressed beyond the stage of being research codes and are now being used by the industry for design and certification calculations for wind turbines. A good overview of the computer programs, which fall into this category, is available in the proceedings of the IEA 'Meeting of Experts'[30].

FUTURE TECHNOLOGICAL DEVELOPMENTS

The advancement of wind turbine technology is leading to next generation wind turbines, which promise significant improvements in performance, reliability and cost. In general, each of these competing turbine designs will probably incorporate many of the following advanced features :

- Advanced airfoils, such as, structurally tailored blades made of soft, flexible materials may also be possible. Such blades would would change shape in response to wind conditions, increasing energy capture and reducing loads, as wind speed controls blade shape;
- Aerodynamic controls, such as, Ailerons, spoiler flaps and double-split flaps are being examined for future use as effective rotor speed brakes;
- Advanced generators using low speed, direct-drive generators could eliminate the need for the gear-box, thereby reducing turbine weight and costs. The generator is likely to be used in combination with variable-speed operation to take advantage of the benefits of latest developments in power electronics; and
- Advanced, expert control systems capable of controlling a single wind turbine, an array of turbines, or an entire power plant should be commonplace in the future. Smart systems can detect wind speed changes and adjust individual turbines throughout a power plant[27].

Although current design standards and certification rules recognise the need to take account of the special wind flow conditions in the situations identified above, there is at present no real guidance available to the industry as to how this should be achieved. Quarton, *et al* recommended that, further measurements and data analysis will undoubtedly be required. Research projects are underway with the aim of providing the necessary information such as making environmental and wind-turbine loading measurements at different sites subject to particularly hostile conditions [31].

CONCLUSION

Remarkable advances in wind power design have been possible due to developments in modern technology. New advanced aerodynamic controls and current research techniques are destined to take wind industry to new heights and glory. One aspect of wind turbines that will increase rapidly is the use of information technology and sophisticated communications for real time monitoring, condition monitoring and control. It is already common for companies to monitor and, if necessary, control machines worldwide via satellite communication. No other commercial plant is operated in this fashion to such an extent [32]. These developments and growing trends towards wind energy signal a promising future for the wind energy industries. With its improved technology and superior economics, experts predict wind power could well capture at least 5% of the world energy market by the year 2020.

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