

Effectual and Lossless Electrical Power Generation Methodology using Wind-Lens Technology

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ABSTRACT

Wind energy is playing a critical role in the establishment of an environmentally sustainable low carbon economy. This paper presents an overview of wind turbine generator technologies and compares their advantages and drawbacks used for wind energy utilization. Traditionally, DC machines, synchronous machines and squirrel-cage induction machines have been used for small scale power generation. For medium and large wind turbines (WTs), the doubly-fed induction generator (DFIG) is currently the dominant technology while permanent magnet (PM), switched reluctance and high temperature superconducting generators are all extensively researched and developed over the years. In this paper, the topologies and features of these machines are discussed with special attention given to their practical considerations involved in the design, control and operation. It is hoped that this paper provides quick reference guidelines for developing wind turbine generation systems.

Keywords: Diffuser, wind turbine, wind lens technology, electrical power and energy recovery system.

1. INTRODUCTION

The utilization of wind energy can be dated back to 5000 B.C. when sail boats were propelled across the river Nile. It was recorded that from 200 B.C. onwards wind was used as an energy source to pump water, grind grain, and drive vehicles and ships in ancient China and Middle East. The first documented windmill was in a book Pneumatics written by Hero of Alexandria around the first century B.C. or the first century A.D. Effectively, these wind mills are used to convert kinetic energy into mechanical energy [1].

The use of wind energy to generate electricity first appeared in the late 19th century but did not gain ground owing to the then dominance of steam turbines in electricity generation. The interest in wind energy was renewed in the mid-1970s following the oil crises and increased concerns over resource conservation. Initially, wind energy started to gain popularity in electricity generation to charge batteries in remote power systems, residential scale power systems, isolated or island power systems, and utility networks.

These wind turbines themselves are generally small (rated less than 100kW) but could be made up to a large wind farm (rated 5MW or so). It was until the early 1990s when wind projects really took off the ground, primarily driven by the governmental and industrial initiatives. It was also in 1990s there seemed a shift of focus from onshore to offshore development in major wind development countries, especially in Europe [2]. Offshore wind turbines were first proposed in Germany in 1930s and first installed in Sweden in 1991 and in Denmark in 1992. By July 2010, there were 2.4 GW of offshore wind turbines installed in Europe. Compared to onshore wind energy, offshore wind energy has some appealing attributes such as higher wind speeds, availability of larger sites for development, lower wind sheer and lower intrinsic turbulence intensity.

But the drawbacks are associated with harsh working conditions, high installation and maintenance costs. For offshore operation, major components should be modernized with additional anti-corrosion measures and de-humidification capacity. In order to avoid unscheduled maintenance, they should also be equipped with fault-ride-through capacity to improve their reliability. Over the last three decades, wind turbines have significantly evolved as the global wind market grows continuously and rapidly. By the end of 2009, the world capacity reached a total of 160 GW [3].

In the global electricity market, wind energy penetration is projected to rise from 1% in 2008 to 8% in 2035. This is achieved simply by developing larger wind turbines and employing more in the wind farm. In terms of the size, large wind turbines of the MW order began to appear in the EU, the US and now in China and India. Typically, the large installed wind turbines in utility grids are between 1.5-5MW whilst 7.5 and 10 MW are under extensive development. Nowadays, modern wind turbines are reliable, quiet, cost-effective and commercially competitive while the wind turbine technologies are proven and mature. At present, technical challenges are generally associated with ever-growing wind turbine size, power transmission, energy storage, energy efficiency, system stability and fault tolerance. Currently, wind power is widely recognized as a main feasible source of renewables which can be utilized economically in large quantity. Taking the United Kingdom for example, the usable offshore wind energy alone is enough to provide three times more than the required electricity consumption in the country, given sufficient support. However, wind power fluctuates by its nature and such applications demand high reliability and high availability while the market is still looking to reduce weight, complexity and operational costs [4].

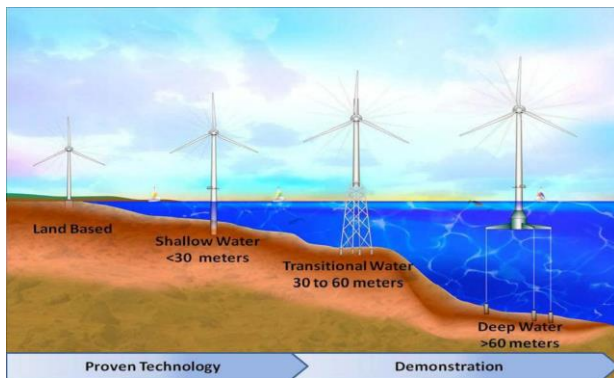


Fig.1. Progression of expected wind turbine evolution to deeper water

2. WIND TURBINES

Clearly, 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, gimbaled or hinged blades, Rigidity: still or flexible, Number of blades: one, two, three or even more, Power control: stall, pitch, yaw or aerodynamic surfaces and Yaw control: active or free. This section focuses only on horizontal-axis wind turbines (HAWTs), which are the prevailing type of wind turbine topology.

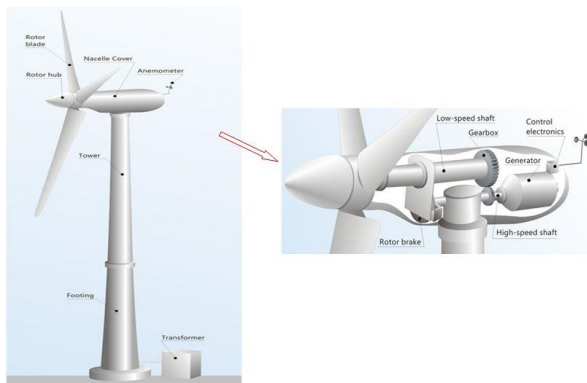


Fig.2. Schematic of a wind turbine generation system

Wind turbines include critical mechanical components such as turbine blades and rotors, drive train and generators. They cost more than 30% of total capital expenditure for offshore wind project. In general, wind turbines are intended for relatively inaccessible sites placing some constraints on the designs in a number of ways. For offshore environments [5], the site may be realistically accessed for maintenance once per year. As a result, fault tolerance of the wind turbine is of importance for wind farm development. One of key components in the wind turbine is its drive train, which links aerodynamic rotor and electrical output terminals. Optimization of wind turbine generators cannot be realized without considering mechanical, structural, hydraulic and magnetic performance of the drive train. Generally, they can be broken down into four types according to their structures: Conventional: gearbox and high speed generator with few

pole pairs, Direct drive: any drive train without a gearbox and low speed generator with many pole pairs, Hybrid: any drive train with a gearbox and the generator speed between the above two types and Multiple generators: any drive train with more than one generator. Drive train topologies may raise the issues such as the integration of the rotor and gearbox/bearings, the isolation of gear and generator shafts from mechanical bending loads, the integrity and load paths. Although it may be easier to service separate wind turbine components such as gearboxes, bearings and generators, the industry is increasingly in favor of system design of the integrated drive train components [6].

3. WIND TURBINE GENERATORS

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 [7]. 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.

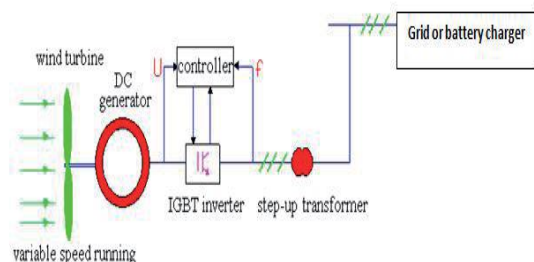


Fig.3. Schematic of a DC generator system

3.1 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. 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 [8]. 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 where the load is physically close to the wind turbine, in heating applications or in battery charging.

3.2 AC Synchronous Generator Technologies

Since the early time of developing wind turbines, considerable efforts have been made to utilize three-phase synchronous machines. AC synchronous WTGs can take constant or DC excitations from either permanent magnets or electromagnets and are thus termed PM synchronous generators (PMSGs) and electrically excited synchronous generators (EESGs), respectively. When the rotor is driven by the wind turbine, a three-phase power is generated in the stator windings which are connected to the grid through transformers and power converters. For fixed speed synchronous generators, the rotor speed must be kept at exactly the synchronous speed. Otherwise synchronism will be lost. Synchronous generators are a proven machine technology since their performance for power generation has been studied and widely accepted for a long time. In theory, the reactive power characteristics of synchronous WTGs can be easily controlled via the field circuit for electrical excitation [9].

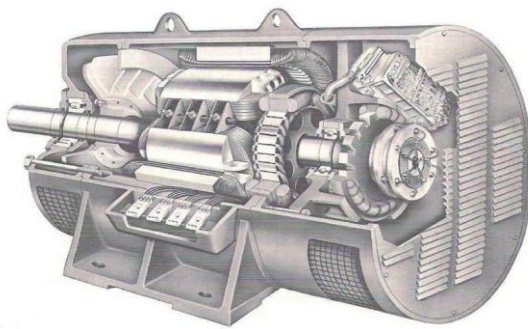


Fig.4. Cutaway of a synchronous generator

Nevertheless, when using fixed speed synchronous generators, random wind speed fluctuations and periodic disturbances caused by tower-shading effects and natural resonances of components would be passed onto the power grid. Furthermore, synchronous WTGs tend to have low damping effect so that they do not allow drive train transients to be absorbed electrically. As a consequence, they require an additional damping element (e.g. flexible coupling in the drive train), or the gearbox assembly mounted on springs and dampers. When they are integrated into the power grid, synchronizing their frequency to that of the grid calls for a delicate operation. In addition, they are generally more complex, costly and more prone to failure than induction generators. In the case of using electromagnets in synchronous machines, voltage control takes place in the synchronous machine while in permanent magnet excited machines, voltage control is achieved in the converter circuit.

In recent decades, PM generators have been gradually used in wind turbine applications due to their high power density and low mass. Often these machines are referred to as the permanent magnet synchronous generators (PMSGs) and are considered as the machine of choice in small wind turbine generators. The structure of the generator is relatively straightforward. The rugged PMs are installed on the rotor to

produce a constant magnetic field and the generated electricity is taken from the armature (stator) via the use of the commutator, slip rings or brushes. Sometimes the PMs can be integrated into a cylindrical cast aluminum rotor to reduce costs. The principle of operation of PM generators is similar to that of synchronous generators except that PM generators can be operated asynchronously. The advantages of PMSGs include the elimination of commutator, slip rings and brushes so that the machines are rugged, reliable and simple. The use of PMs removes the field winding (and its associated power losses) but makes the field control impossible and the cost of PMs can be prohibitively high for large machines [10]. Because the actual wind speeds are variable, the PMSGs cannot generate electrical power with fixed frequency. As a result, they should be connected to the power grid through ACDC-AC conversion by power converters. That is, the generated AC power (with variable frequency and magnitude) is first rectified into fixed DC and then converted back into AC power (with fixed frequency and magnitude). It is also very attractive to use these permanent magnet machines for direct drive application. Obviously, in this case, they can eliminate troublesome gearboxes which cause the majority of wind turbine failures. The machines should have large pole numbers and are physically large than a similarly rated geared machine.

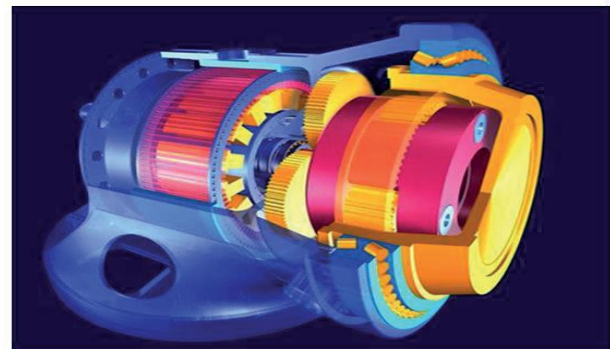


Fig.5. Cutaway of a permanent magnet synchronous generator

A potential variant of synchronous generators is the high-temperature superconducting generator. The machine comprises the stator back iron, stator copper winding, HTS field coils, rotor core, rotor support structure, rotor cooling system, cryostat and external refrigerator, electromagnetic shield and damper, bearing, shaft and housing. In the machine design, the arrangements of the stator, rotor, cooling and gearbox may pose particular challenges in order to keep HTS coils in the low temperature operational conditions.

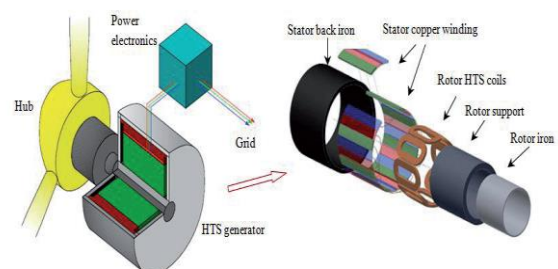


Fig.6. Schematic of a HTS synchronous generator system

Superconducting coils may carry 10 times the current than conventional copper wires with negligible resistance and conductor losses. Without a doubt, the use of superconductors would eliminate all field circuit power loss and the ability of superconductivity to increase current density allows for high magnetic fields, leading to a significant reduction in mass and size for wind turbine generators. Therefore, superconducting generators provide much promise in high capacity and weight reductions, perhaps suited better for wind turbines rated 10 MW or more. In 2005, Siemens successfully launched the world's first superconducting wind turbine generator, which was a 4MW synchronous generator [11]. However, there are many technical challenges to face especially for the long-life, low-maintenance wind turbine systems. For instance, there is always a necessity to maintain cryogenic systems so that the time to cool down and restore operation following a stoppage will be an additional issue.

3.3. AC Asynchronous Generators

Whilst conventional power generation utilizes synchronous machines, modern wind power systems use induction machines extensively in wind turbine applications. These induction generators fall into two types: fixed speed induction generators (FSIGs) with squirrel cage rotors (sometimes called squirrel cage induction generators-SQIGs) and doubly fed induction generators (DFIGs) with wound rotors. When supplied with three-phase AC power to the stator, a rotating magnetic field is established across the airgap. If the rotor rotates at a speed different to synchronous speed, a slip is created and the rotor circuit is energized. Generally speaking, induction machines are simple, reliable, inexpensive and well developed. They have high degree of damping and are capable of absorbing rotor speed fluctuations and drive train transients (i.e. fault tolerant). However, induction machines draw reactive power from the grid and thus some form of reactive power compensation is needed such as the use of capacitors or power converters. For fixed-speed induction generators, the stator is connected to the grid via a transformer and the rotor is connected to the wind turbine through a gearbox. The rotor speed is considered to be fixed (in fact, varying within a narrow range). Up until 1998 most wind turbine manufacturers built fixed-speed induction generators of 1.5 MW and below. These generators normally operated at 1500 revolutions per minute (rpm) for the 50 Hz utility grid, with a three-stage gearbox. SCIGs led the wind turbine market until the last millennium, overtaken by the wide adoption of DFIGs.

Nowadays, over 85% of the installed wind turbines utilize DFIGs and the largest capacity for the commercial wind turbine product with DFIG has increased towards 5MW in industry. In the DFIG topology, the stator is directly connected to the grid through transformers and the rotor is connected to the grid through PWM power converters. The converters can control the rotor circuit current, frequency and phase angle shifts. Such induction generators are capable of operating at a wide slip range (typically $\pm 30\%$ of synchronous speed). As a result, they offer many advantages such as high energy yield, reduction in mechanical stresses and power fluctuations, and controllability of reactive power. For

induction generators, all the reactive power energizing the magnetic circuits must be supplied by the grid or local capacitors. Induction generators are prone to voltage instability. When capacitors are used to compensate power factor, there is a risk of causing self-excitation. Additionally, damping effect may give rise to power losses in the rotor. There is no direct control over the terminal voltage (thus reactive power), nor sustained fault currents.

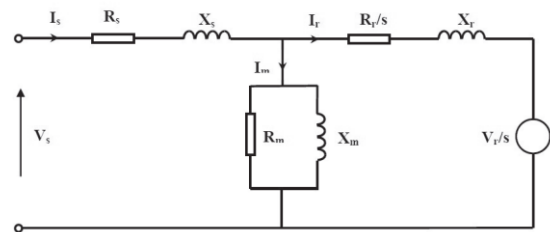


Fig.7. Per-phase equivalent circuit of the DFIG

3.4 Switched Reluctance Generator Technologies

Switched reluctance WTGs are characterized with salient rotors and stator. As the rotor rotates, the reluctance of the magnetic circuit linking the stator and rotor changes, and in turn, induces currents in the winding on the armature (stator).

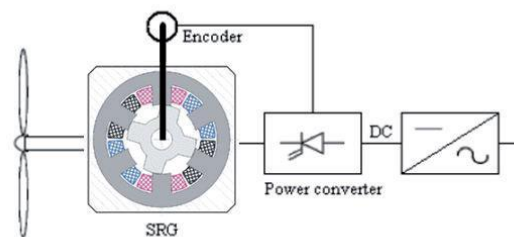


Fig.8. Schematic of a switched reluctance generator system

The reluctance rotor is constructed from laminated steel sheets and has no electrical field windings or permanent magnets. As a result, the reluctance machine is simple, easy to manufacture and assembly. An obvious feature is their high reliability because they can work in harsh or high-temperature environments. Because the reluctance torque is only a fraction of electrical torque, the rotor of switched reluctance is generally large than other with electrical excitations for a given rated torque. If reluctance machines are combined with direct drive features, the machine would be extremely large and heavy, making them less favorable in wind power applications.

4. DESIGN CONSIDERATIONS AND CHALLENGES

Generally speaking, wind turbine generators can be selected from commercially available electrical machines with or without minor modifications. If a wind turbine design is required to match a specific site, some key issues should be taken into account. These include: Choice of machines, Type of drive train, Brush topology, Rated and operating speeds, Rated and operating torques, Tip speed ratio, Power and current, Voltage regulation (synchronous generators), Methods of starting, Starting current (induction generators), Synchronizing (synchronous generators), Cooling arrangement, Power factor and reactive power compensation

(induction generators), Power converter topology, Weight and size, Protection (offshore environment) and Capital cost and maintenance. Among these design considerations, the choice of operating speed, drive type, brush topology, and power converter are focused and further analyzed in details.

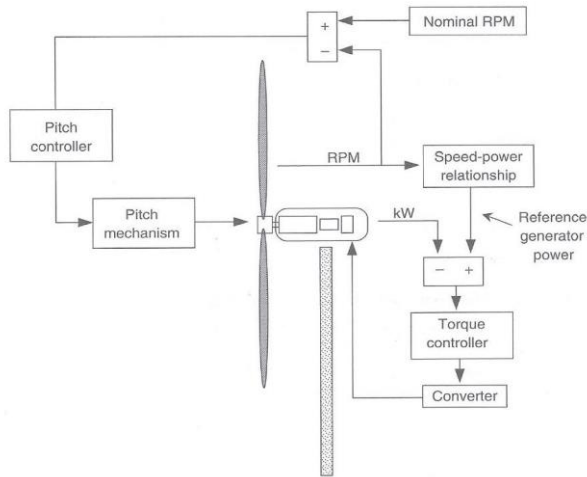


Fig.9. Variable speed control system

4.1 Fixed or Variable Speed

Clearly, it is beneficial to operate WTGs at variable speed. The reasons are several. When the wind speed is below rated, running the rotor speed with the wind speed and keeping the tip speed ratio constant ensure that the wind turbine will extract the maximum energy. Variable speed operation helps reduce fluctuating mechanical stresses on the drive train and machine shaft, the likelihood of fatigue and damage as well as aerodynamically generated acoustic noise. The rotor can act as a regenerative storage unit (e.g. flywheel), smoothing out torque and power fluctuations prior to entering the drive train. Direct control of the air-gap torque also aids in minimizing gearbox torque fluctuations. Since there is a frequency converter between the wind turbine generator and the power grid, it becomes possible to decouple the network frequency and the rotor rotational speed. This permits variable speed operation of the rotor and controllability of air-gap torque of the machine. Furthermore, variable speed operation enables separate control of active and reactive power, as well as power factor. In theory, some wind turbine generators may be used to compensate the low power factor caused by neighboring consumers. In economic terms, variable speed wind turbine can produce 8-15% more power than fixed speed counterparts. Nonetheless, the capital costs will be increased arising from the variable speed drive and power converters, as well as increased complicity and control requirements.

In principle, variable speed operation can be achieved mechanically by the use of differential gearboxes or continuously-variable transmission systems, based on the control of speed and angular speed of gyroscopes. But the general practice is to achieve this goal by electrical means. There are two major methods in use: broad range and narrow range variable speed. The former refers to a wide operational range from zero to the full rated speed where the latter refers to a narrow operational range between a fractions (up to $\pm 50\%$) of synchronous speed. In reality, this latter range is

practically sufficient and can saving significant costs on power electronic converters.

In the design of variable-speed wind turbines, three control aspects in association with the wind speed need to consider. First, a constant optimized tip speed should be maintained to achieve maximum aerodynamic efficiency by varying the rotor speed with the actual wind speed. Second, the rotor speed should be maintained constant after the rotor has reached its rated speed but the power has not, in the case of moderate winds. When the wind speed is higher, the control is to maintain a constant rated power via the pitch angle control or stall control. Whilst using the pitch angle control, the blade pitch is varied to control the rotor speed together with the generator torque.

4.2 Direct or Geared Drive

In a geared wind turbine, the generator speed increases with the gear ratio so that the reduction in machine weight is offset by the gain in gearbox weight. For instance, the wind turbine operates at a speed of 15 rpm and the generator is designed to operate 1200 rpm (for 60 Hz). An up-speed gearbox of 1:80 is required to match the speed/torque of the turbine with these of the generator. However, historically, gearbox failures are major challenges to the operation of wind farms. This is especially true for offshore wind turbines which are situated in harsh and less-accessible environments. Because of this, direct drive systems are increasingly desired in new wind turbine systems. One example is the excited synchronous generator with wound field rotor is a well-established design in the marketplace; and another may be a popular neodymium magnet generator design which also attracts much attention in the marketplace. Obviously, direct drive configuration removes the necessity for gears and the related reliability problems. Therefore, some wind turbine manufacturers are now moving toward direct-drive generators to improve system reliability. Since wind turbine generators are operated with power electronic converters, direct drive topology can provide some flexibility in the voltage and power requirements of the machines. Nonetheless, a drawback of the direct drive is associated with the low operating speed of the turbine generator. As the nominal speed of the machine reduces, the volume and weight of its rotor would increase approximately in inverse proportion for a given power output.



Fig.10. Example of a direct drive MW wind turbine generator

4.3 Brushed or Brushless Topology

In general, DC machines, wound rotor synchronous generators, wound rotor induction generators all employ commutators, brushes or slip rings to access the rotating rotor circuits. Consequently, routine maintenance and replacement lead to some difficulties in wind power applications, especially for offshore installations. Clearly it would be particularly desirable to rid of any components physically connected to the rotating parts of wind turbines. There are several ways of achieving this. Taking the DFIG for example, brushless doubly-fed generators (BDFGs) can be a solution. They use two windings on the stator (a power winding and a control winding) with different pole numbers. The rotor can be of squirrel cage type and an indirect coupling of the two stator windings is established through the rotor. It is also possible to use a reluctance rotor in this topology where the machine has become a brushless reluctance generator. By modifying the conventional machines, a higher reliability is achieved due to the absence of the brushes and slip rings. The penalty is the use of two machines in a machine case.

4.4 Two-Level, Multi-Level or Matrix Converter

Power electronics is recognized as being a key and enabling component in wind turbine systems. Broadly, there are three types of converters widely used in the wind market. These are two-level, multi-level and matrix converters. Two level power converters are commonly called “back-to-back PWM converters. They include two voltage source inverters (with PWM control scheme) connected through a DC capacitor. This is a mature technology but suffers from high costs, high switching loss and large DC capacitors. Any power converters having three or more voltage levels are termed “multi-level converters”.

5. CONCLUSIONS

Wind energy has attracted much attention from research and industrial communities. One of growth areas is thought to be in the offshore wind turbine market. The ongoing effort to develop advanced wind turbine generator technologies has already led to increased production, reliability, maintainability and cost-effectiveness. At this stage, the doubly-fed induction generator technology (equipped with fault-ride-through capacity) will continue to be prevalent in medium and large wind turbines while permanent magnet generators may be competitive in small wind turbines. Other types of wind turbine generators have started to penetrate into the wind markets to a differing degree. The analysis suggests a trend moving from fixed-speed, geared and brushed generators towards variable-speed, gearless and brushless generator technologies while still reducing system weight, cost and failure rates. This paper has provided an overview of different wind turbine generators including DC, synchronous and asynchronous wind turbine generators with a comparison of their relative merits and disadvantages. More in-depth analysis should be carried out in the design, control and operation of the wind turbines primarily using numerical, analytical and experimental methods if wind turbine generators are to be further improved. Despite continued research and development effort, however, there are still numerous technological, environmental and economic

challenges in the wind power systems. In summary, there may not exist the best wind turbine generator technology to tick all the boxes. The choice of complex wind turbine systems is largely dictated by the capital and operational costs because the wind market is fundamentally cost-sensitive. In essence, the decision is always down to a comparison of the material costs between rare-earth permanent magnets, superconductors, copper, steel or other active materials, which may vary remarkably from time to time.

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