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Power Electronic Systems Used in Renewable Energy systems: Recent Trends and Future Challenges

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Abstract - Power electronics systems used in wind energy conversion systems (WECS) are very important in modern variable speed large wind turbines and have become a focal point in the research of devices and their control mechanism. Most modern wind turbines operate at variable speed. This paper provides an in-depth review of power electronics systems used to interface variable speed wind turbine to the electric grid. The different variable speed induction generator-converter combinations are compared on the basis of topology, efficiency, cost and control techniques. Comparisons of the variable-speed and fixed-speed wind turbines (WT) are discussed. Moreover, attempts are made to highlight future trends and future challenges in power electronic systems in wind power generation.

Keywords *- Wind power, Permanent magnet synchronous generator, Doubly fed induction generator, Matrix converter, Direct power control.*

I. INTRODUCTION

Wind power, which has been proved as a potential source for generation of electricity with minimal environmental impact, is the fastest-growing source for electric power generation and it is expected to remain so in future. At the end of 2006, the wind installed capacity stands at over 74223 MW which is more than 15,197 megawatts (MW) from the capacity in 2005 [1]. World Wind Energy Association (WWEA) expects 160 GW to be installed worldwide by 2010. Despite constraints facing supply chains for wind turbines, the annual market for wind continued to increase at the staggering rate of 32% following the 2005 record year, in which the market grew by 41%. In terms of economic value, the wind energy sector has now become firmly installed as one of the important players in the energy markets [1].

With the advancement of aerodynamic designs, wind turbines those can capture several megawatts of power are available. When such wind energy conversion systems (WECSs) are integrated into the grid, they produce a substantial amount of power, which can supplement the base power generated by thermal, nuclear, or hydro power plants. Harnessing wind energy for electric power generation is an area of research interest and at present, the emphasis is given to the cost-effective utilization of this energy resource for quality and reliable power supply. There have been many advances in wind turbines and most modern wind turbines operate at variable speed. Because of the improved reliability of power electronic converters, however, it is possible to vary the frequency to the ac generator and, thereby, allow for variable-speed operation. By adjusting the speed, the wind turbine can be optimized to run at near peak power production for various wind speeds. It was found that the variable-speed system produced 60% more energy compared to a fixed-speed system [2]. Different schemes have been proposed to operate wind turbines at variable speeds for optimizing wind turbine operation. This paper provides an in-depth review of power electronics systems used in wind energy conversion system. The different variable speed induction generator-converter combinations are compared on the basis of topology, efficiency, cost and control techniques. Comparisons of the variable-speed and fixed-speed wind turbines (WT) are discussed. Moreover, attempts are made to highlight future trends and future challenges in power electronic systems in wind power generation.

II. WIND ENERGY BACKGROUND

Human efforts to harness wind for energy date back to the ancient times, when they used to sail the ships and boats. Later, wind energy served the mankind by providing the energy for girding mills and water pumps. During its transformation from these crude and heavy devices to today’s efficient and sophiscated machines, the technology went through various phases of development [54]. In Holland, several decisive improvements were made on windmills in the 16th century, leading to a new type of mill, so called 'Dutch windmill' [55]. The era of wind electric generators began close to 1900's. The first modern wind turbine, specifically designed for electricity generation was constructed in Denmark in 1890. By 1910, several hundreds of such machines were supplying electrical power to the villagers in Denmark. By about 1925, the wind electric generators became commercially available in the American market [54]. Intensive research on wind turbines started during 1950 in Germany, Denmark and USA. However, during this period, electricity generated from wind costs 8-10 times than that of fossil fuels. But oil crisis in 1970's forced the world to think about wind power generation. In 1980s, the cost of electricity from utility-scale wind power projects was as high as 30 cents per kWh, at present, the cost of generating electricity from wind power ranges from 3 to 6

A. Wind Turbine Characteristics

The amount of power captured from a wind turbine is governed by:

Where *P* is the turbine power, p is the air density, *A* is the swept turbine area, C_P is the coefficient of performance and v_w is the wind speed. The coefficient of performance of a wind turbine is influenced by the tip speed ratio (TSR), A.

Where O is the turbine rotational speed and *r* is the turbine radius. A typical relationship, as shown in Fig. 1, indicates that there is one specific TSR at which the turbine is the most efficient [3]. In order to achieve maximum power, the TSR should be kept at the optimal operating point for all wind speeds.

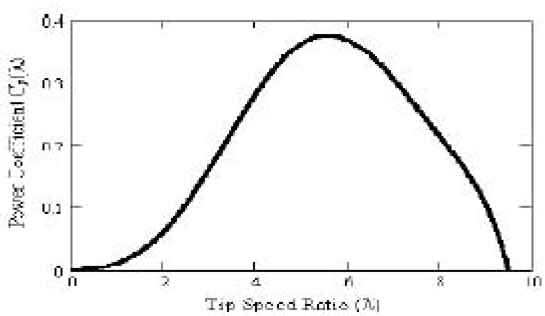

Fig. 1 : Power Coefficient Vs Tip Speed Ratio

The turbine output power can be plotted with respect to the turbine rotational speed for different wind speeds, as shown in Fig. 2 [4]. The curves indicate that the maximum power point increases and decreases as wind speed rises and falls. Normally, a variable speed wind turbine follows C_{max} to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at A_{opt}. Then, it operates at the rated power with power regulation during high wind periods by active control of the blade pitch angle or passive regulation based on aerodynamic stall. Efficiency is an important issue in wind power when comparing different systems because losses reduce the average power produced by the wind energy converter and, thereby, they reduce the revenue.

B. Wind Turbine Maximum Power Extraction

To allow the turbine to transfer a maximum fraction of available wind power for fluctuating wind velocities incident upon the turbine blades, it is desirable to track the P_{opt} curve shown in Fig. 2. This control objective i.e. maximize power extraction can be achieved by mainly two different control strategies for a given speed. First one is by measuring the wind velocity and adjust the turbine rotating speed to keep the power coefficient at its maximum value. Other technique employs a maximum power point tracking (MPPT) algorithm which searches for the active power reference to the PQ-controller from the table of maximum power versus mechanical speed.

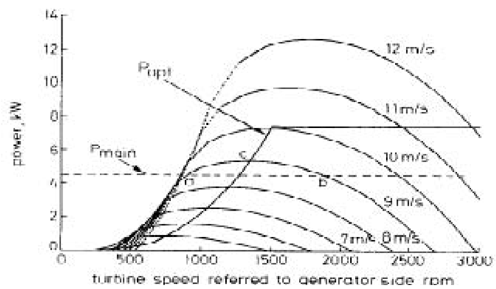

Fig. 2 Wind Turbine characteristic

Alternatively, a slightly different control-scheme, in which active power is measured and mechanical speed is calculated by the inverse MPT-characteristic, is used. In this case, the calculated speed is sent as speed-reference to a speed-controller. MPPT algorithm is more suitable and preferred, since it employs the measured power, which is more accurate than measuring wind velocity, to use as reference for rotating speed of turbine. If neither the turbine characteristics nor the wind speed are known, an MPPT algorithm can be implemented using operational seeking method based on behavioral rules linked to power and speed variations [5].

III. VARIABLE SPEED VS FIXED SPEED WECS

The important development in the technology of wind turbines are the variable speed systems which are technically more advanced than constant speed systems. Each of the turbine designs has its own benefits and drawbacks.

A. Fixed Speed WECS

In a fixed-speed wind energy conversion system, the generator is directly connected to the electrical grid. A soft-starter is normally used in order to reduce the inrush current during start-up. Also a reactive power compensator is needed to reduce (almost eliminate) the reactive power demand from the turbine generators [6]. The rotor speed of fixed-speed wind turbine is, in principle, determined by a gearbox and the pole-pair of the generator. The fixed-speed wind turbine system has often two fixed speeds. This is accomplished by using two generators with different ratings and pole pairs, or it can be a single generator with two windings having different ratings and pole pairs. This leads to increase aerodynamic capture as well as reduced magnetizing losses at low wind speeds. This system (one or two-speed) is the "conventional" concept used by many Danish manufacturers in the 1980s and 1990s [7]. With a fixed speed WECS, it may be necessary to use aerodynamic.

The advantage of a fixed speed turbine is that it is relatively simple and therefore the investment cost tends to be slightly lower. These turbines have to be more mechanically robust than other designs, because of the higher structural loads involved. For a fixed-speed system the turbulence of the wind will result in power variations, and thus affects the power quality of the grid. Further, noise can be a problem, because the noise level is strongly related to the blade tip speed and hence to the rotational speed of the rotor, which, of course, cannot be changed in constant speed turbines. This problem is, however, alleviated by using a generator whose number of pole pairs can be changed, allowing the turbine to run at lower rotational speed when wind speed is low.

B. Variable Speed WECS

To connect a variable speed wind turbine to the grid, a power electronic converter is always necessary. This causes extra investment and additional losses due to the converter. On the other hand, with a converter-fed variable speed wind turbine, adaptation of the rotor speed to the actual wind speed in order to maximize energy production is possible for a specific wind speed. Although, the electrical efficiency decreases due to the losses in the power electronics that are essential for variable speed operation, there is also a gain in aerodynamic efficiency due to variable speed operation. The aerodynamic efficiency gain exceeds the electrical efficiency loss, overall resulting in a higher energy yield [8]. Another advantage is that variable speed turbines also allow the grid voltage to be controlled, as the reactive power generation can be varied.

For a variable-speed WT, it is possible to control the rotor speed. By this way there is less mechanical stress and the power fluctuations caused by wind variations can be absorbed with rotor speed variations. Hence, the power quality impact caused by variable-speed wind turbine can be improved compared to the fixed-speed turbine [2]. Noise problems are reduced as well, because the turbine runs at low speed when there is low wind. The drawbacks of variable speed are that the built-in power electronics are sensitive to voltage dips caused by faults and/or switching and that they are more expensive. However, using a variable speed generating system can also give major savings in other subsystems of the turbine, such as lighter foundations in offshore applications, limiting the overall cost increase. Further, the price of power electronic components is dropping steadily in recent years. The variable speed concepts take the greatest benefit from a high tip speed ratio. This means, that a variable speed machine will pay off better, if a high tip speed ratio is selected. But the drawback is the high acoustic noise produced by blades due to the high speed.

IV. GENERATORS AND POWER CONVERTER TOPOLOGIES

A generator is a device which converts mechanical (rotational) energy to the electrical energy. Mechanical connection to the turbine rotor is through the main shaft. The connection may be by direct drive, or using a gearbox. The use of a gearbox allows matching of the generator speed to that of the turbine. This allows some optimization of generator characteristics, but a disadvantage of the gearbox is being a mechanical component which is subjected to wear and tear and, in some cases, relatively unreliable [9].

A. Doubly-Fed Induction Generator

Doubly-fed induction generators (DFIG) are provided with three phase windings on the rotor and on the stator. They may be supplied with energy at both rotor and stator terminals. The DFIG is one of the main techniques used in variable speed windmills. Due to its many advantages such as the improved power quality, high energy efficiency and controllability, reduced power converter rating, etc. the variable speed wind turbine using a doubly fed induction generator (DFIG) is becoming a popular concept [2],[6],[45]. If a wound rotor induction machine is used, it is possible to control the generator by accessing the rotor circuits.

A significant advantage in using doubly fed induction generators (DFIG) is the ability to output more than its rated power without becoming overheated. It is able to transfer maximum power over a wide speed range in both sub- and super-synchronous modes [4]. Another major advantage of the DFIG, which has made it popular, is that the power electronic equipment only has to handle approximately one-third of stator power, whilst the majority of the power flows through the stator. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the total system power apart from the cost saving of using a smaller converter. Static power converters for the rotor circuit of a DFIG may be classified as follows.

1) DFIG with DC current Link AC-AC Converter

Traditionally, DC current link AC-AC converter consists of a machine side diode rectifier with a DC choke and a source side line commutated current-source thyristor inverter as shown in Fig. 3 [10]. When a diode rectifier is used on the machine side, the power flow is from the machine to the power grid (unidirectional). Thus, DFIG can operate as a motor sub-synchronously and as a generator super-synchronously (two quadrant operations). Going through or operation at synchronous speed is not possible. Also, the current harmonics content in the rotor and in the stator is high, and the power factor on the source side is rather modest [11]. To solve this problem, the diode rectifier can be replaced with another thyristor rectifier (SCR) [12-15]. The inclusion of a second SCR allows bidirectional power flow and thus provide for four quadrant operations. The generator reactive power demand can be supplied by the rotor-side converter. The optimum performance is obtained by adjusting the gear ratio of the gear box to its optimum.

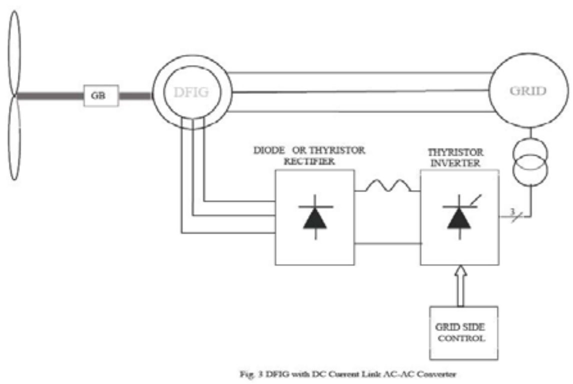

Fig. 3 : DFIG with DC current Link AC-AC Converter

Major drawbacks of this approach include firing and commutation problems with the converter and the presence of large DC choke, and poor dynamic performance. The configurations with thyristor DC current link AC-AC current and, respectively , with thyristor cycloconverters seem to be merely of historical interest, as their reactive power drainage and current harmonics content are no longer acceptable in terms of power quality standards [11].

2) DFIG with Back-to-Back PWM Converter

The back-to-back PWM-VSI, which is widely used in WECS, is a bi-directional power converter consisting of two conventional PWM-VSIs as shown in Fig.4. PWM techniques have been used to decrease the harmonic distortion and to increase controllability of the system, as well as to improve the dynamic performance. To achieve full control of the grid current, the DC-link voltage must be boosted to a level higher than the amplitude of the grid line-to-line voltage. The power flow of the grid side converter is controlled in order to keep the DC-link voltage constant, while the control of the generator side converter is set to meet the magnetization demand and the reference speed. Due to popularity of this scheme, several control techniques of the two level back-toback PWM-VSI in the wind turbine application is described in literature [4] [16-25].

The vector control [4],[16]-[20] is very extensively used in DFIG. The objective of the vector-control scheme for the grid-side PWM converter is to keep the DC-link voltage constant regardless of the magnitude and direction of the rotor power, while keeping sinusoidal grid currents. It may also be responsible for controlling reactive power flow between the grid and the grid-side converter. The vector-control scheme for the rotor-side PWM converter ensures decoupling control of stator-side active and reactive power drawn from the grid. The reference value of the stator-side active power is obtained via a look-up table for a given generator rotor speed, which enables the optimal power tracking for maximum energy capture from the wind [4, 17]. PWM modulation techniques or alternatively space vector modulation (SVM) can be used in order to achieve a better modulation index [18].

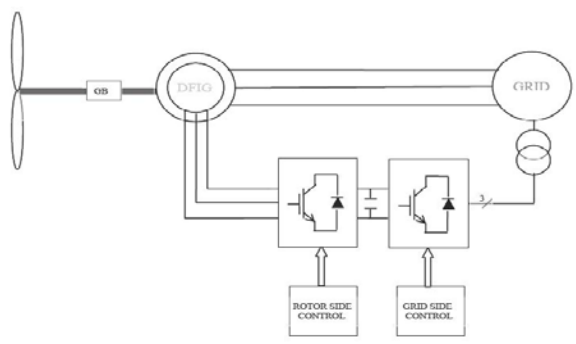

Fig. 4 : DFIG with Back-to-Back PWM Converter

Other control schemes aided by a rotor speed encoder obtain excellent tracking results. However these encoders are expensive and the cost due to lost accuracy without the encoder may not be as large. The performance of this scheme depends on the computational accuracy of the stator flux and the accuracy of the rotor position information derived from the position encoder. Alignment of the position sensor is moreover, difficult in a doubly-fed wound rotor machine [21]. Position sensorless vector control methods have been proposed by several researchers in the recent past [19], [22]– [25]. In [22], a dynamic torque angle controller, which uses integration of the PWM rotor voltage to compute the rotor flux, is proposed. Hence, the satisfactory performance cannot be achieved at or near synchronous speed. Most of the other proposed methods make use of the measured rotor current and coordinate transformations for estimating the rotor position [19],[23]-[25]. Varying degree of dependence on machine parameters is observed in all these strategies.

The direct power controls (DPC) methods [21], which are advanced closed loop controllers using hysteresis approach, is based on the measurement of active and reactive power on the grid side and. These controllers directly trigger a sequence of voltage vectors in the rotor side converter based on power errors and on position of the rotor flux. In this method, the applied voltage vectors can be determined from another table to eliminate coordinate transformation. This method is inherently position sensorless and does not depend on machine parameters like stator/rotor resistance. It is also capable of starting on the fly and runs stably even at zero rotor frequency. The main drawback of back-to-back PWM-VSI is the high cost and less overall life due to presence of heavy and bulky DC link capacitor. Another important drawback is the switching losses. The high switching speed to the grid may also require extra EMI-filters.

3) DFIG with Matrix Converter

A superior version of direct AC-AC converter used in DFIG is matrix converter as shown in Fig.5. The matrix converter is capable of converting the variable AC from the generator into constant AC to the grid in one stage.

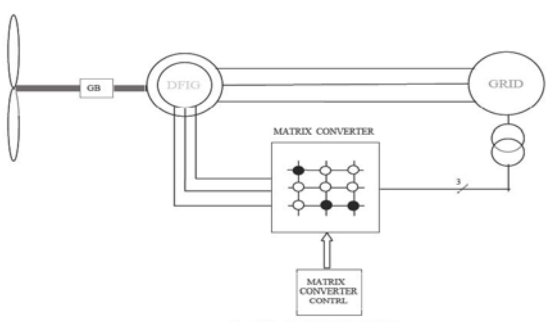

Fig. 5 : DFIG with MATRIX Converter

B. Squirrel- Cage Induction Generator

In WECS having squirrel cage induction generator (SCIG), the stator winding is directly connected to network through a four-quadrant full power rating converter as it needs bidirectional power flow to supplies the reactive power to maintain the machine magnetization. These machines are relatively inexpensive, but robust and require less maintenance. When induction machines are operated using vector-control techniques, fast dynamic response and accurate torque control are obtained [31]. The configurations with thyristor DC current link AC-AC current and, respectively, with thyristor cycloconverters seem to be merely of historical interest, as their reactive power drainage and current harmonics content are no longer acceptable in terms of power quality standards[11]. The cascaded AC-AC PWM converter as shown in Fig. 6 is available in MW range with up to 100% reactive power capabilities. Several control techniques are reported in literatures [31]-[35].

In [31], the vector control structure based on a standard indirect rotor flux orientated (IRFO) control of the induction machine is used in which d-q current and voltage values are referred to the reference frame aligned to the rotor flux. Reference [32] uses a simple V/Hz control scheme with the frequency being set on the speed and optimum power of the turbine produced at that speed. In [33], a fuzzy control system is used to get the maximum energy capture for a given wind velocity. A second fuzzy controller programs the machine flux for light load efficiency improvement, and a third fuzzy controller gives robust speed control against wind gust and turbine oscillatory torque. The advantages of fuzzy logic control are parameter insensitivity, fast convergence and acceptance of noisy and inaccurate signals.

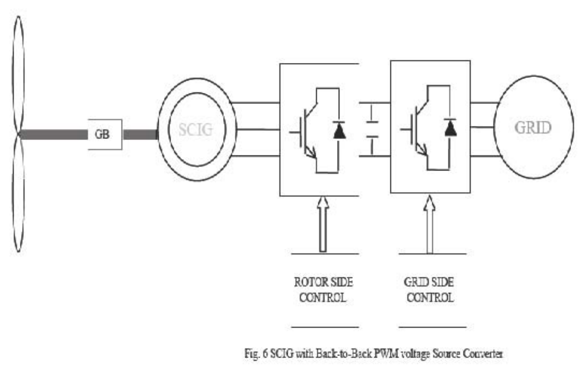

Fig. 6 : SCIG with BACK-to-BACK PWM Converter

In [34], a sensorless control structure based on a direct rotor flux-oriented (DRFO) vector-control system is discussed. Speed estimation, obtained from a model reference adaptive system (MRAS), is used to control the electrical torque of the induction machine. A V/F control strategy is used in the low-speed region for starting and driving the WECS. In order to tune the MRAS system and compensate for the variation of the machine parameters, an estimation of the rotational speed is obtained from the rotor slot harmonics (RSH). A vector controlled boost type PWM converter [35] is developed using PI type fuzzy logic controller which takes DC voltage error and the change in DC voltage error as inputs. Some papers [36]-[37] use the matrix converter for SCIG WECSs.

C. Permanent Magnet Synchronous Generator (PMSG)

Future of wind turbine technology lies in PMSG. With the permanent magnet, high power densities can be achieved in a less space. Hence, the generators become much more compact with high efficiencies. Notable advantage is absence of gearbox and its acoustic noise. No external excitation current, thus, no power electronic circuitry is needed. Earlier PMSG are only suitable for low-power range, but now they are available in the MW range. The main limitation for PMSG is the high cost of the materials for the magnet. Also, generators with permanent magnet excitation have a poor power factor and can be compensated by inverter technology [55]. Mainly there are two types of converter topologies are employed for PMSG as shown in Fig 7 and Fig. 8.

Fig. 7 shows PMSG connected to a three-phase rectifier with intermediate DC link [38-39], and a boost DC/DC converter [40-42]. Incorporating an extra DC/DC converter gives the following advantages [3]:

- Control of generator-side DC-voltage through variation of the switching ratio,
- Maintains appropriate inverter-side DC-voltage,
- Allows for selective harmonic elimination (SHE) switching, giving reduced losses, and
- Inverter no longer needs to control DC-voltage, and has more flexible control.

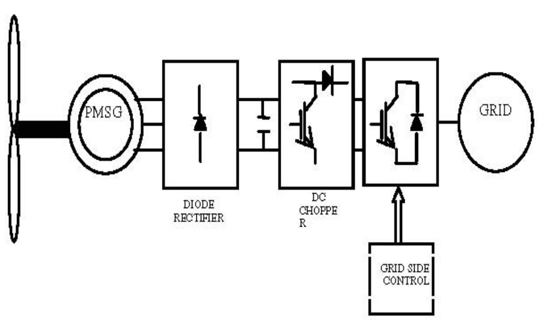

Fig. 7 PMSG with Diode Rectifier and DC Chopper

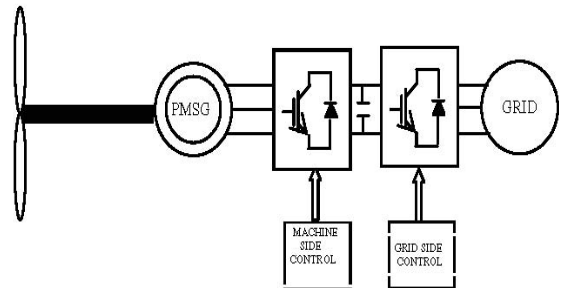

Fig. 8 : PMSG with BACK-to-BACK PWM Converter

Other scheme using PMSG is shown in Fig.8. In this topology, the back-to-back PWM converters are connected between PMSG and the network [43-45]. Vector control can be easily applied for decoupled control. The DC link voltage is maintained constant by grid side inverter control. In [44], a vector control is performed for both converters. The generator reactive current component is calculated and imposed on the generator in order to minimize power losses, both in the generator and power converter, along the whole operating range. The power capability of an inverter is also discussed. In [45], control strategy independent of turbine parameters, to extract the maximum power from the grid connected machine is given. To reduce the cost and to increase efficiency, only eight switches and two DC link capacitors are proposed, instead of twelve switches and a single capacitor. In order to operate the PMSG at unity power factor, the three-phase reference currents which are in phase with the respective phase voltages are generated. These reference currents are in phase with the respective grid voltages. This is achieved by a separate PLL [45]. For PMSG, rectifier with boost converter is found more cost effective solution for AC-DC converter than 3-phase IGBT PWM converter.

V. FUTURE TRENDS AND CHALLENGES

At present, wind turbines are available in the power range 5 to 6 MW. Besides the high costs, the main problem is the weight and outer dimensions of the components. Trend towards the gearless turbines is increasing as the gearbox is one of the weakest links, requiring frequent maintenance, and refurbishment or replacement. These wind turbines (gearless) are characterized by large, with diameters up to 5 meter, multi-pole synchronous generators. Hybrid designs are also obtainable, e.g. one-stage step-up gearbox followed by a less massive multi-pole generator [46]. The market share of variable speed rotor technology, including modern power electronics, will increase further in following area:

A. Multilevel Inverters

Trends on wind-turbine market make the multilevel converter suitable for modern high-power wind-turbine applications. The increase of voltage rating allows for connection of the converter of the wind turbine directly to the wind-farm distribution network, avoiding the use of a bulky transformer [47]. In [7] the different multilevel-converter topologies are classified. The reduced content of harmonics in the input and output voltages is highlighted together with the reduced electromagnetic interference (EMI) [47]. Moreover, the multilevel converters have the lowest demands for the input filters or alternatively reduced number of commutations [49]. Even though the conducting losses are higher in the multilevel converter, the overall efficiency depends on the ratio between the switching and the conducting losses [48]. The most commonly reported disadvantage of the three level converters with split DC-link is the voltage imbalance between the upper and the lower DC-link capacitor. Application of multilevel inverters to WECS with experimental validation may be found in [50-51].

B. FACTS and HVDC Applications in Wind Power Systems

One of the main trends in wind turbine technology is offshore installation. Offshore wind turbines can/will generally yield some 50% more energy than a turbine placed on a nearby onshore site [47]. Offshore wind will focus on reliability, remote control, low noise, easy and low cost transport to the grid, and high installed power per wind turbine (up to or more than 10 MW)[46]. In [52] a review of the important modeling techniques employed for developing FACTs controllers and examines the role of HVDC-Light transmission in exploiting the off-shore wind energy resources. Reference [53] investigates the application of FACTS devices to enhance the dynamic and transient performance of power systems which includes a large wind farm.

C. Control Schemes

There are so many conventional and non-conventional control schemes are being suggested for wind energy system. There are still a commercialization of these controller needed. Various controllers are proposed to improve the performances but the interaction of these controllers with the power electronic system used in the wind turbines must be examined before implementation.

D. Optimization

Grid connected WECS must operate in an optimal way. There are various devices used in WECS and to optimally utilize them, optimal power flow (OPF) problem is to be solved and the required objective can be achieved with wind turbine power electronics systems [57]. The OPF is a mixed-integer, nonlinear problem and can be solved.

VI. CONCLUSIONS

Wind energy has a potential to play an important role in the future energy supply in many areas of the world. Within the last 10 years, wind turbine technology has reached a very reliable and mature level and will continue to remain so as power electronic technology continues to advance. This paper presents a comprehensive review of various WECS used in wind power. Power electronics systems used in combination with PMSG, DFIG and SCIG, along with different control schemes for variable speed operation and to maximize turbine output power have been described in detail. It is found that the matrix converter and multilevel inverter are the more serious competitors to Back-to-Back converter. Comparisons of the variable-speed and fixed-speed wind turbines (WT) are presented, which clearly indicates the superiority of variable-speed WECS. Moreover, attempts are made to highlight future trends and challenges in power electronic systems in wind power generation.

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