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A review of power converter topologies for wind generators

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Abstract

Wind energy conversion systems have become a focal point in the research of renewable energy sources. This is in no small part due to the rapid advances in the size of wind generators as well as the development of power electronics and their applicability in wind energy extraction. This paper provides a comprehensive review of past and present converter topologies applicable to permanent magnet generators, induction generators, synchronous generators and doubly fed induction generators. The many different generator–converter combinations are compared on the basis of topology, cost, efficiency, power consumption and control complexity. The features of each generator–converter configuration are considered in the context of wind turbine systems.
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Keywords: Induction generators; Power electronics; Wind energy

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Abbreviations: DFIG, doubly fed induction generators; IG, induction generators; MMF, magneto–motive force; MPPT, maximum power point tracking; MRAS, model reference adaptive system; PI, proportional–integral; PLL, phase lock loop; PMSG, permanent magnet synchronous generator; PWM, pulse width modulation; RPS, rotary phase shifter; RSH, rotor slot harmonics; SCR, silicon controlled rectifier; SG, synchronous generator; SHE, selective harmonic elimination; SVM, space vector modulation; TSR, tip-speed to wind speed ratio; VSC, voltage source converter; VSI, voltage source inverter; VSV, voltage space vectors; WECS, wind energy conversion system

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1. Introduction

Power extracted from wind energy contributes a significant proportion of consumers' electrical power demands. For example, 20% of the entire electricity consumption in Denmark is provided by wind energy [1]. In recent years, many power converter techniques have been developed for integrating with the electrical grid. The use of power electronic converters allows for variable speed operation of the wind turbine, and enhanced power extraction. In variable speed operation, a control method designed to extract maximum power from the turbine and provide constant grid voltage and frequency is required. A wide range of control schemes, varying in cost and complexity, have been investigated for all the previously considered conversion systems. All control schemes integrated with the power electronic converter are designed to maximize power output at all possible wind speeds. The wind speeds range from the cut-in speed to the rated wind speed, both of which are specific to the size and type of generator used in the wind energy conversion system (WECS).

In this paper, the possible combinations of converter and generator topologies for permanent magnet generators, caged rotor induction generators, synchronous generators and doubly fed induction generators including more specifically wound rotor induction machines are discussed and some of the possible control strategies are touched upon. This paper serves as a concise summary and comparison of the state of art regarding power electronic topologies and wind energy conversion systems.

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2. Wind energy background

The amount of power captured from a wind turbine is specific to each turbine and is governed by

$$P_t = \tfrac{1}{2}\rho A C_P v_w^3 A, \tag{1}$$

where P_t is the turbine power, ρ 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 to wind speed ratio or TSR given by

$$TSR = \frac{\omega r}{v_w}, \tag{2}$$

where ω 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 most efficient [2]. In order to achieve maximum power, the TSR should be kept at the optimal operating point for all wind speeds. The turbine power output can be plotted versus the turbine rotational speed for different wind speeds, an example of which is shown in Fig. 2. The curves indicate that the maximum power point increases and decreases as wind speed rises and falls. In the following sections, the various generator–converter combinations that are able to obtain maximum power output for varying wind speeds are discussed.

3. Permanent magnet synchronous generators

Permanent magnet excitation is generally favored in newer smaller scale turbine designs, since it allows for higher efficiency and smaller wind turbine blade diameter. While recent

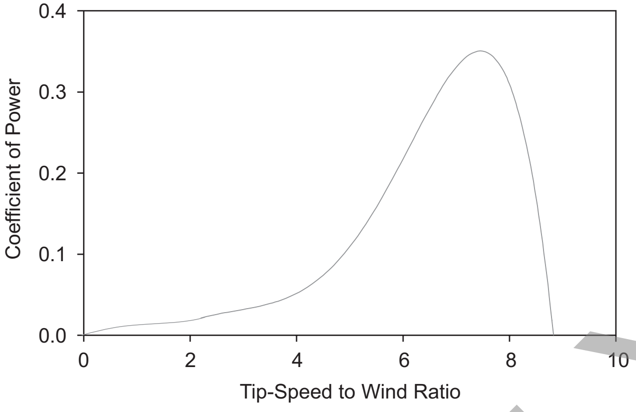

Fig. 1. Typical coefficient of power curve.

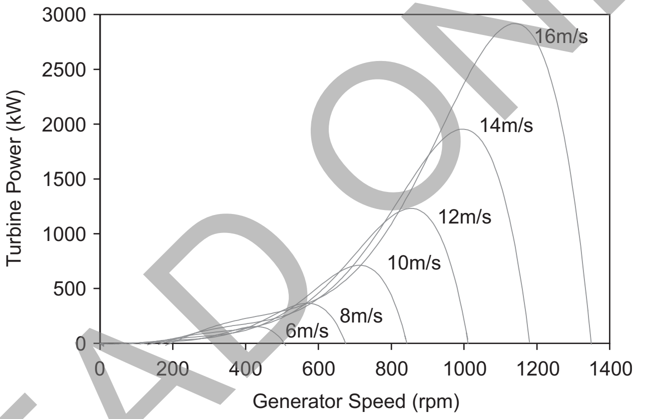

Fig. 2. Turbine output power characteristic.

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research has considered larger scale designs, the economics of large volumes of permanent magnet material has limited their practical application. The primary advantage of permanent magnet synchronous generators (PMSG) is that they do not require any external excitation current. A major cost benefit in using the PMSG is the fact that a diode bridge rectifier may be used at the generator terminals since no external excitation current is needed. Much research has been performed using a diode rectifier [3–10,13–15]; however, this leaves many options for the remainder of the power converter and its control, some of which are shown in Fig. 3.

3.1. Thyristor supply-side inverter

Using a thyristor-based grid-side inverter allows continuous control of the inverter firing angle, regulating turbine speed through the DC-link voltage; hence, obtaining optimum energy capture [3]. Advantages of this scheme include lower device cost and higher available power rating than hard-switched inverters. A major drawback to this inverter is

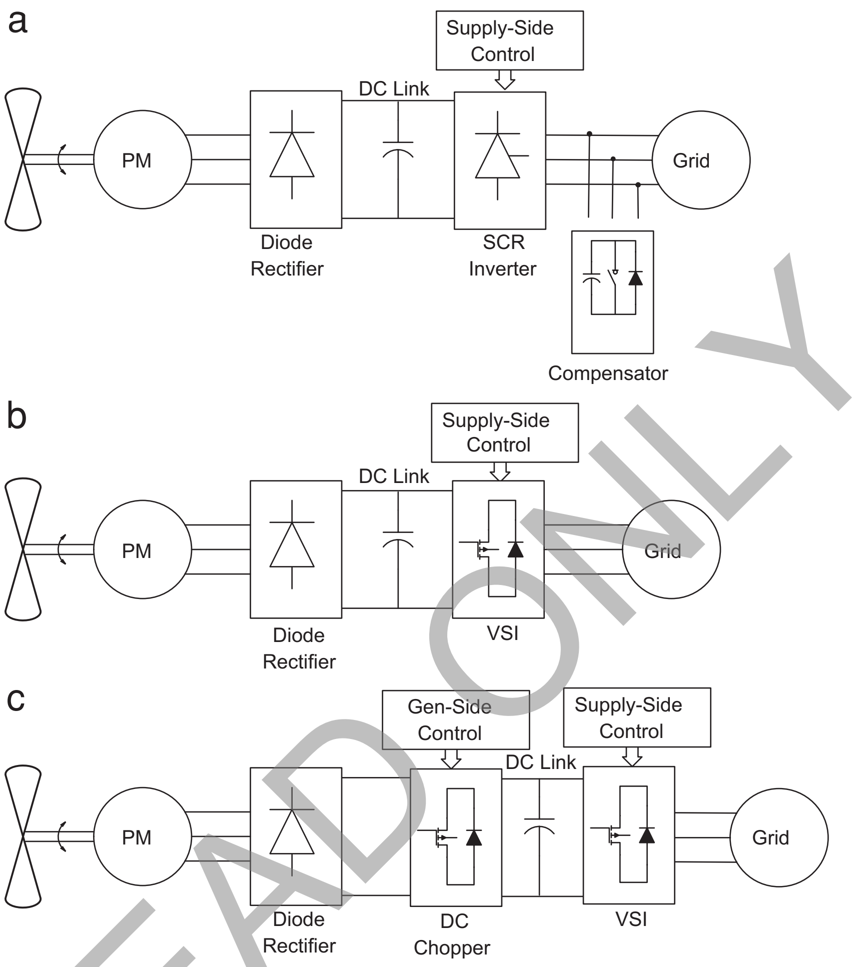

Fig. 3. PMSG with diode rectifier converter options.

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the need for an active compensator for the reactive power demand and harmonic distortion created, as shown in Fig. 3a. A voltage source converter (VSC) is used for the compensator and the error signal between the reference and actual compensator current is used to drive the pulse width modulated (PWM) control [3].

3.2. Hard-switching supply-side inverter

Various control strategies that can be applied to the converter in Fig. 3b have been discussed [4]. A proposed control involves the manipulation of the modulation index of the reference sinusoidal signal applied to the PWM generator. This is achieved by determining the DC-link voltage by a power mapping technique that contains the maximum power versus DC voltage characteristic. The control system is further improved by using a derivative control on the stator frequency, since it also changes with change in DC-link voltage [4]. This control is compared with maximum power point tracking (MPPT), which includes an anemometer, a wind prediction control scheme and a fixed-voltage scheme. The anemometer measures the wind speed and aids in providing the wind power reference to the MPPT controller. The reference power is compared with the actual DC power extracted in which the result is used to determine the new operating DC voltage. The current control loop of the inverter receives the new operating DC voltage and outputs an instantaneous driving signal for the PWM [4]. In wind prediction methods, autoregressive statistical models are commonly used. The system considers energy captured in the previous time frame to predict the wind speed value for the next time frame set. Under fixed-voltage control, the voltage of the inverter is fixed at a targeted optimum wind speed.

In comparing the four control methods, the fixed voltage scheme was used as the reference since it was least efficient. The MPPT with anemometer setup proved to be superior, obtaining 56–63% of energy available. However, the proposed method using sensor-less control was not far behind, obtaining 55–61% of the total energy available from the wind.

3.3. Intermediate DC/DC converter stage

The use of a voltage source inverter (VSI) accompanied by a DC/DC converter is investigated [5,6], depicted in Fig. 3c. This setup is also compared to the converter shown in Fig. 3b [7]. Incorporating an extra DC/DC converter gives the following advantages:

1. control of generator-side DC-voltage through variation of the switching ratio,
2. maintains appropriate inverter-side DC-voltage,
3. allows for selective harmonic elimination (SHE) switching, giving reduced losses,
4. inverter no longer needs to control DC-voltage, and has more flexible control.

The inverter power control can be achieved by regulating the magnitude of the fundamental line current and the phase angle between the line current and line voltage [5]. The controller is configured such that the VSI is switched at the frequency of the triangular carrier signal and its output harmonics are well defined. For every shaft speed, optimum values of DC voltage and current can be identified corresponding to the maximum available turbine power [6]. The DC/AC voltage ratio and power angle are used as control variables that are tuned to control the power, and ultimately the speed of the generator. The inverter control can also be implemented to keep the DC-link constant and vary the reactive power in a manner that attains maximum real power transfer to the grid [6]. Results show that the thyristor-based inverter with active compensator is best suited for strong AC systems since it relies on the system to ensure commutation [6]. However, both the VSI and DC/DC–VSI systems are capable of integrating with both strong and weak AC systems.

Other control strategies have been discovered for this converter [8,9]. The DC/AC inverter can control the active and reactive power delivered to the grid via control of the q-axis and d-axis current, respectively [8]. The q-axis reference current is determined by the error in the DC-link voltage, and is then compared with the actual current. The phase angle of the utility, used in power factor control, is detected using software phase lock loop (PLL) in a d–q synchronous reference frame. Power factor control creates the d-axis reference current allowing it to be compared with the actual d-axis current. The error in both reference frame currents are used to create the d–q-axis reference voltages used in

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space vector PWM control. Using the voltage equation governing a boost-up DC/DC chopper and a proportional–integral (PI) controller, the duty ratio of the chopper switch may be determined for any particular optimum point [8]. The inverter-side DC voltage remains constant set by the grid voltage giving the advantage of flexible transfer of active and reactive power to the grid.

A slight modification to the DC-link shown in Fig. 3c is made by including a battery. The battery allows charging during night time when load demand is usually lower. An immediate advantage is a constant DC-link voltage, therefore, controlling the chopper output current to its maximum value giving maximum output power [9]. To perform the control, a relationship between the output power and duty cycle of the chopper is used. Starting from an arbitrary point, the duty cycle can be continuously and slowly adjusted between a specific range searching for the maximum power point. It is found that the control system began losing efficiency at high speeds; this was due to the phase lag between the DC current and duty ratio [9]. A faster sampling rate would help correct this problem.

3.4. Back-to-back PWM converters

The use of two, 6-switch, hard-switched converters, with a DC-link capacitor, Fig. 4a, has been explored [10]. The generator side rectifier is controlled through a PI controller such that the *d*-axis current is held to zero to obtain maximum electrical torque with minimum current. A MPPT is used in determining the optimum rotor speed for each wind speed to obtain maximum rotor power. In contrast, the grid side inverter controls the line current to be sinusoidal through a hysteresis controller. The DC-link voltage is also controlled by a PI controller, via the grid side inverter [10].

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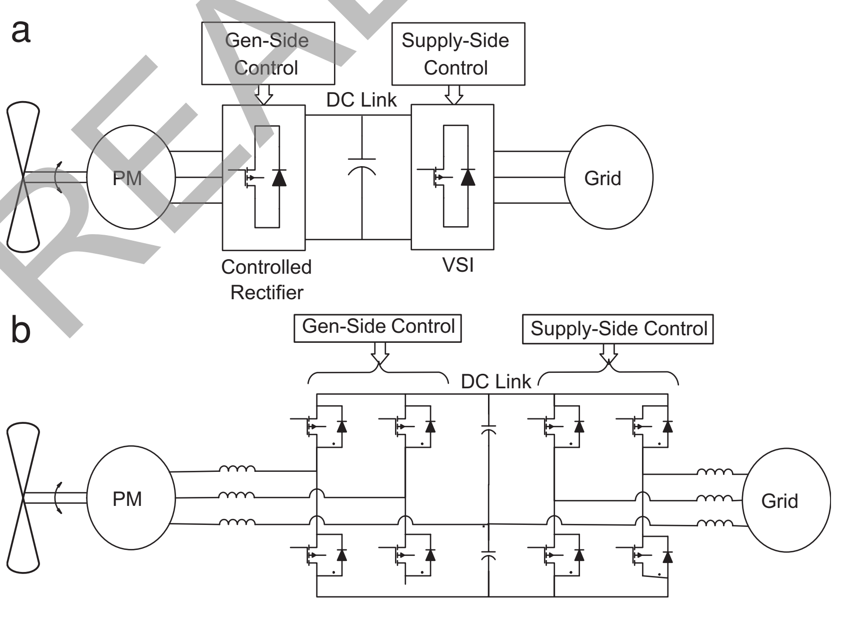

Fig. 4. PMSG with back-to-back PWM converter schemes.

More recently, a converter using two B-4 converters and two DC-link capacitors has been developed, shown in Fig. 4b [11]. Again MPPT calculates the output power of the generator by measuring the DC-link current and voltage, and then alters the operating point by increasing or decreasing the reference current magnitude. The MPPT control is performed on the generator side rectifier. The grid-side control sets the inverter current through a PI controller and the DC-voltage error. The current error is used to drive the inverter switching signals. A PLL is used on each side to ensure unity power factor is maintained throughout the entire system [11].

3.5. Unconventional schemes

A rather unconventional scheme using a PMSG has been discussed [12]. The system uses a rotary phase shifter (RPS) as a frequency converter. The RPS can adjust the angular velocity of the generator at a low cost in comparison to a power electronic device. A flywheel is also used as power stabilizer; it has a lifetime that is not limited unlike the use of a battery. As this is an uncommon method, more details can be found in [12].

Recently, research has been performed to solve DC-link shortage problems under low wind speed conditions. By placing three switches between the diode rectifier legs and middle point of the DC-link capacitor, the voltage at low winds can be increased. During low wind speeds, the switches are turned on and off alternately, keeping the system symmetrical while increasing the voltage. The switches are not used during high winds to avoid frequent over-voltages. This is not a common practice but one worth noting, and further details can be found in [13]. Another modification to the converter system in Fig. 3b can be made to ensure energy flow is unidirectional from generator to grid. By placing a simple diode in between the capacitive DC-link and the inverter, energy flow is restricted due to the reverse blocking capabilities of the diode [14].

4. Doubly fed induction generators

As the PMSG has received much attention in wind energy conversion, the doubly fed induction generator has received just as much consideration, if not more. 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. The DFIG along with induction generators are excellent for high power applications in the MW range. More importantly, converter power rating is reduced since it is connected to the rotor, while the majority of the power flows through the stator.

4.1. Static Kramer drive and SCR converter methods

The static Kramer drive consists of a diode rectifier on the rotor side and a line commutated inverter connected to the supply side [15], (Fig. 5). With this converter, a sliding mode control is developed which provides a suitable compromise between conversion efficiency and torque oscillation smoothing. The controller regulates the thyristor inverter firing angle to attain the ideal compromise. The sliding mode control law forces the generator torque to be a linear function of the generator speed around the

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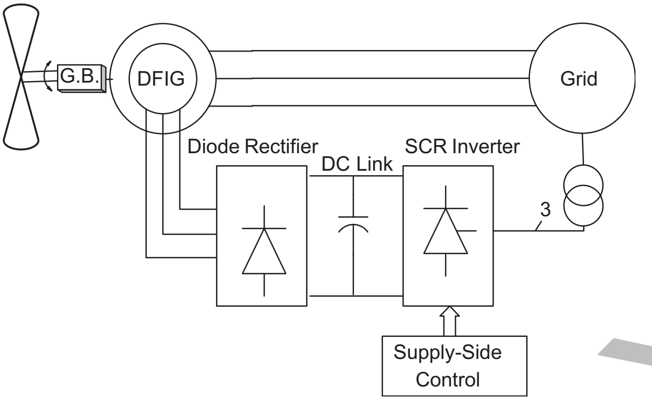

Fig. 5. DFIG with static Kramer drive.

operating point of maximum power transfer [15]. This converter is only able to provide power from both stator and rotor circuits, under super-synchronous operation. To solve this problem, other methods replace the diode rectifier with another thyristor rectifier (SCR) [16,17].

The inclusion of a second SCR allows the generator reactive power demand to be satisfied by the rotor-side converter system. When connected to the wind turbine, it is shown that optimum performance is obtained by adjusting the gear ratio, of the gear box, to its optimum value [16]. In comparison to the Kramer drive, this system produces more power output due to the lack of reactive power available with a diode rectifier. More detailed control of the two rectifiers is given in [17]. A range of both firing angles for each mode of operation (sub- and super-synchronous modes) is given as a plot showing the optimum firing angle at different wind speeds giving greatest power transfer. It is discovered that between 7.5 and 8.5 m/s, maximum power can be generated in both sub- and super-synchronous modes [17]. Major drawbacks of this approach include firing and commutation problems with the rotor-side converter and harmonic distortion to the grid, created by the supply-side thyristor converter.

4.2. *Back-to-back PWM converters*

A more technologically advanced method using back-to-back converters has been developed, Fig. 6. Much work has been presented using this type of converter [18–22]. Although the converter used in these works are extremely similar, great differences lie within the control strategy and complexity.

One option is to apply vector control to the supply-side converter, with a reference frame orientated with the *d*-axis along the stator voltage vector [18,19]. The supply-side converter is controlled to keep the DC-link voltage constant through regulation of the *d*-axis current. It is also responsible for reactive power control through alteration of the *q*-axis current [18,19]. As for the rotor side, the choice of decoupled control of the electrical torque and the rotor excitation current is presented [18]. The machine is controlled in a synchronously rotating reference frame with the *d*-axis orientated along the stator-flux vector, providing maximum energy transfer. Conversely, in [19], the rotor current was decomposed into *d*–*q*

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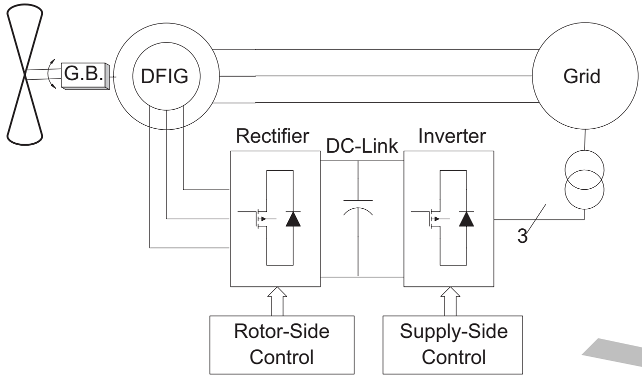

Fig. 6. DFIG with back-to-back PWM converters.

components, where the *d*-axis current is used to control the electromagnetic torque and the *q*-axis current controls the power factor. Both types of rotor-side converter control employ the use of PI controllers. PWM switching techniques can be used [18], or alternatively space vector modulation (SVM) is used in order to achieve a better modulation index [19].

Often 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 use of speed sensors has been described [20,21]. To accompany the capacitor in the DC-link, a battery may be used as a storage device. With the extra storage device, the supply-side converter now controls the transfer of real power between the grid and the battery, as the DC voltage is now fixed [20]. The supply side controller is made up of three PI controllers, one for outer loop power control, and the other two for the *d*–*q*-axis inner current control loop. Energy is stored during high winds and is exported to the grid during calm conditions to compensate for the drop in stator power. During long periods of high or low wind speeds, the control algorithm is modified to regulate the bus voltage until the conditions change. In this case, the rotor-side converter is gated in order to control the real and reactive power of the machine. Another different option for rotor control has been identified [21]. The algorithm searches for the peak power by varying the rotor speed, and the peak power points are recognized as zero slopes on the power-speed curves. The control works continuously, as a significant shift in power causes the controller to shift the speed which in turn causes the power to shift once again. Once the change in power no longer exceeds the minimum set value, the controller takes no further action. Once again, *d*–*q*-axis control is used to control the real and reactive power of the machine. It is important to ensure that the dynamics of the speed controller are not extremely fast, else large transients in generator torque may occur [21].

The typical control objectives described above can be attained through control theory based on voltage space vectors (VSV). The application of certain voltage vectors may accelerate the rotor flux, and increase the active power generated by the stator. Other voltage vectors may also increase or decrease the rotor flux magnitude, resulting in a reduction in the reactive power drawn by the stator and an improved power factor. This direct power control method requires a series of tables to determine which of the six

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sectors the controller is operating on. From the choice of sector, the applied voltage vectors can be determined from another table. The controller tables and details are provided in [22].

A final control scheme, for the back-to-back PWM converter scheme, uses information on shaft speed and turbine output power to estimate the wind speed [23]. The turbine output power is described as a function of TSR. The roots of the equation are solved to determine the optimum TSR within a specific range. With the estimated wind speed and optimal TSR, the new reference of the generator output power and shaft speed is obtained. The system is commanded to the desired shaft speed and the output power is again measured, regurgitating the control. This control is applied to a brushless DFIG, which gives reduced cost in comparison to machines with brushes and slip-rings [23].

4.3. Matrix converter

The matrix converter is capable of converting the variable AC from the generator into constant AC to the grid in one stage (Fig. 7). Two distinct advantages arise from this topology, the converter requires no bulky energy storage or DC-link and control is performed on just one converter. The utilization of a matrix converter with a DFIG has been explored [24,25]. The use of a stator–flux oriented control was employed on the rotor matrix converter. The d-axis current was aligned with the stator–flux linkage vector. Simple PI controllers can be employed to control the d–q-axis currents. The regulation of the d-axis current allows for control of the stator-side reactive power flow, where as the q-axis current helps regulate the stator-side active power [24].

Another option is to control the rotor winding voltage, which consequently manipulates the power factor of the DFIG [25]. The matrix converter consists of nine bi-directional switches (18 total), arranged in a manner such that any input phase may be connected to any output phase at any time. Each individual switch is capable of rectification and inversion. The matrix converter is controlled using double space vector PWM, employing the use of input current and output voltage SVM. The details of this method exceed the scope of this paper and can be further examined in [25]. One of the major drawbacks of a matrix converter is that 18 total switches are required, causing an increase in converter semiconductor cost.

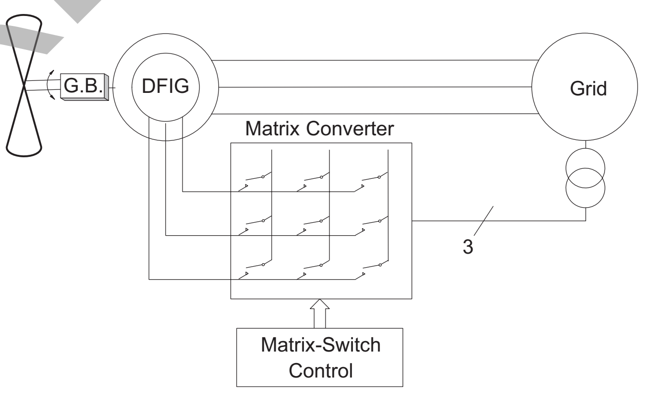

Fig. 7. DFIG with matrix converter.

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5. Induction generators

The use of induction generators (IG) is advantageous since they are relatively inexpensive, robust and they require low maintenance. The nature of IG is unlike that of PMSG, they need bi-directional power flow in the generator-side converter since the induction generator requires external reactive power support from the grid. The use of back-to-back PWM converters, Fig. 8, along with the implementation of one or more fuzzy logic controllers is a consistent converter-control combination [26–28]. The advantages of fuzzy logic control are parameter insensitivity, fast convergence and acceptance of noisy and inaccurate signals. A PI type fuzzy logic controller takes in the DC voltage error and change in DC voltage error [26]. The controller outputs the *d*-axis reference current used in real power flow control. In a similar manner, the *q*-axis current is kept zero to maintain unity power factor.

A control scheme using three fuzzy logic controllers has also been investigated in [27]. The first controller tracks the generator speed with the wind velocity to extract maximum power. The second controller programs the machine flux for light load efficiency improvement. More specifically, the machine rotor flux can be reduced from the rated value to reduce the core loss and thereby improve the efficiency. The rotor flux may be reduced by continually decreasing the magnetizing current until the maximum power increase is obtained. The third controller gives robust speed control against wind gust and turbine oscillatory torque. Unlike the second controller, the third fuzzy logic controller is always active.

In other work, a PI fuzzy controller is also used [28]; however, rotor slot harmonics (RSH) are used for speed estimation. The rotor slots interact with the magnetizing component of the air-gap magneto-motive force (MMF), generating harmonics that are dependant on the machine rotational speed [28]. Once the algorithm locates the frequency of the RSH through a look-up table, the rotational speed is found through a series of calculations. Along with the use of RSH, the control system also utilizes sensor-less control through a model reference adaptive system (MRAS) observer to estimate the rotational speed. More information on this system is located in [28], as the details will not be discussed here. A control option for the supply-side converter includes real and reactive power control. A reference frame orientated along the supply voltage rotating vector allows for real power control through *d*-axis current control and *q*-axis manipulation controls the reactive power [28]. The aforementioned control is proven to track fast changes in rotational speed with high accuracy, a favorable characteristic for systems employing a stall controlled wind turbine. This control algorithm can react quickly to wind

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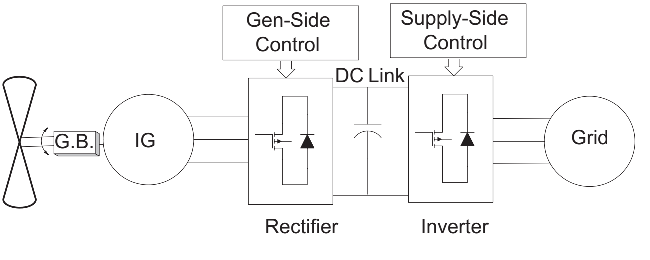

Fig. 8. Induction generator with back-to-back converters.

gusts and may be utilized to control the amount of mechanical power and torque input to the generator. These are common concerns for stall controlled wind turbines as operation over rated power may cause damage to the generator and power electronic converter.

An atypical WECS converter setup has been explored [29]. Instead of the usual back-to-back PWM converter scheme, the authors use a fixed-capacitor thyristor-controlled reactor static VAR compensator at the generator terminals to regulate its voltage. The mechanical input power is controlled using the blade pitch angle. The design techniques used for the control systems are based on the state space linearized model of the system. Two controllers, a state feedback controller and output feedback controller were designed. The output feedback control is preferred since all the output signals are available for measurement and an observer is not needed as in the state feedback control [29].

A comparison between the use of a wound rotor induction machine and a caged rotor induction machine, both of identical size, has been performed [30]. Both the squirrel cage induction machine and wound rotor six pole slip ring induction machine have a rated voltage of 415 V. The two generators are identically rated for 300 kW and have a rated speed of 1000 RPM. The comparison ensures validity with the use of identical converter types in each of the systems. The separate designs were each tested under identical variable wind conditions. A variable wind speed profile was created to model a region with an average wind speed of 12 m/s during peak wind season. It is shown, under the same wind conditions, that the wound rotor induction machine outputs 35 kWh of energy over 10 min, where as the caged induction machine only outputs 28.5 kWh in 10 min. The higher cost of the wound rotor induction machine, due to possible need of slip rings, is compensated by the reduction in the sizing of the power converters and the increase in energy output. The DFIG is superior to the caged induction machine, due to its ability to produce above rated power.

6. Synchronous generators

Finally, the application of synchronous generators (SG) in wind power generation has also been researched. A brief description of one possible converter-control scheme is given for a small wind energy conversion system. The use of a diode rectifier along with a DC/DC boost stage and inverter as a power electronic interface for grid connection has been discussed [31]. The converter is similar to Fig. 3c, except a SG replaces the PMSG. In this scheme, the DC-link voltage is controlled by using the amplitude of the three-phase inverter voltages and the phase displacement angle of the inverter. The linearized currents and DC-link voltage of the inverter can be obtained by means of state equations [31]. Controller performance improvements are achieved over the traditional power angle control. For low power systems, the existence of a winding circuit in the rotor may be a drawback as compared with PMSG. Although PMSG are commonly used for low-power application, the more recent larger systems use SG.

In large systems, the energy from the SG are most commonly converted through back-to-back PWM voltage source inverters, similar to Fig. 8. The supply side PWM inverter allows for control of real and reactive power transferred to the grid. The generator side converter is used for electromagnetic torque regulation [32,33]. The controllers used in these systems are designed to achieve maximum power transfer to the grid. These generators have a high efficiency since the whole of the stator current is employed during electromagnetic torque production. Another advantage is the minimization of stator

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current through the direct control of generator power factor, In comparison to IG, the use of SG is advantageous since they are self-excited machines and the pole pitch of the machine can be smaller. As a result both DFIG and SG are preferred for high power applications.

7. Summary of wind energy conversion systems

A summary of the different generator–converter topologies available for wind energy conversion is shown in Table 1. The cost of the overall system increases as the complexity

Table 1
Summary of wind energy conversion systems

Generator (power range)	Converter options	Device count (semiconductor cost)	Control schemes
PMSG (kW)	Diode bridge/SCR inverter/ compensator	DC-Link cap. 12 ontrollable switches (moderate)	Simple firing angle control of one converter
	SCR rectifier/SCR inverter	DC-link cap. 12 controllable switches (moderate)	Simple firing angle control of both converters
	Diode bridge/Hard-switching inverter	DC-link cap. 6 controllable switches (low)	Power mapping technique including stator frequency derivative control MPPT, wind prediction control
	Diode bridge/DC boost/ Hard-switching inverter	DC-Link cap. 7 controllable switches (Low)	Vector control of supply side inverter DC Voltage control via chopper duty ratio
	Back-to-back hard-switching inverters	DC-Link cap. 12 controllable switches (moderate)	MPPT, vector control of both converters
	Back-to-back hard-switching inverters (reduced switch)	2 DC-link caps. 8 controllable switches (low)	Generator controlled through MPPT inverter current controlled through PI controllers
DFIG (kW–MW)	Diode bridge/SCR inverter	DC-link cap. 6 controllable switches (low)	Sliding mode control
	SCR rectifier/SCR inverter	DC-link cap. 12 controllable switches (Moderate)	Dual thyristor firing angle control
	Back-to-back hard-switching inverters	DC-Link cap. 12 controllable switches (moderate)	Vector control of rotor and supply side space vector modulation or PWM MPPT, space vector control
	Matrix converter	18 controllable switches (high)	Vector control of rotor and supply side double space vector PWM switching
IG (kW–MW)	Back-to-back hard-switching inverters	DC-link cap. 12 controllable switches (moderate)	Vector control, use fuzzy logic controllers use rotor slot harmonics and model reference adaptive system
SG (kW–MW)	Diode bridge/DC boost/ Hard-switching inverter	DC-link cap. 7 controllable switches (low)	Phase angle displacement control supply voltage control
	Back-to-back hard-switching inverters	DC-link cap. 12 controllable switches (moderate)	Supply real and reactive power control generator electromagnetic torque control

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of the power electronic converter increases. The intricacy of the controller design also affects cost; for example, the use of MPPT techniques would cost more than a simple look-up table method. However, higher order control and converter designs may increase efficiency of the overall system. The inclusion of a DC-boost stage helps reduce the control complexity of the grid inverter at a small increase in cost. Likewise, replacing the diode rectifier with a controlled rectifier allows for a wider range of control of both the generator and grid real and reactive power transfer. In order to maximize the benefits of the wind energy conversion system, a compromise between efficiency and cost must be obtained.

In addition Table 2 lists the various generators discussed in this paper and outlines the advantages and disadvantages of each [34–41]. PMSG offer the highest efficiency and are self-exciting machines and are therefore suitable for small-scale designs. However the cost of magnet material becomes an issue for large-scale designs even though magnet production costs have experienced a decrease. DFIG offers a vast reduction in converter size however they are susceptible to grid disturbances since their stator windings are directly connected to the grid. The SG allows for independent control of both real and

Table 2
Advantages and disadvantages of generator types

Generator type	Advantages	Disadvantages
Permanent magnet synchronous generator	• Flexibility in design allows for smaller and lighter designs • Higher output level may be achieved without the need to increase generator size • Lower maintenance cost and operating costs, bearings last longer • No significant losses generated in the rotor • Generator speed can be regulated without the need for gears or gearbox • Very high torque can be achieved at low speeds • Eliminates the need for separate excitation or cooling systems	• Higher initial cost due to high price of magnets used • Permanent magnet costs restricts production of such generators for large scale grid connected turbine designs • High temperatures and sever overloading and short circuit conditions can demagnetize permanent magnets • Use of diode rectifier in initial stage of power conversion reduces the controllability of overall system
Asynchronous generator	• Lower capital cost for construction of the generator • Known as rugged machines that have a very simple design • Higher availability especially for large scale grid connected designs • Excellent damping of torque pulsation caused by sudden wind gusts • Relatively low contribution to system fault levels	• Increased converter cost since converter must be rated at the full system power • Results in increased losses through converter due to large converter size needed for IG • Generator requires reactive power and therefore increases cost of initial AC–DC conversion stage of converter • May experience a large in-rush current when first connected to the grid • Increased control complexity due to increased number of switches in converter

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Table 2 (*continued*)

Generator type	Advantages	Disadvantages
Doubly fed induction generator	• Reduced converter cost, converter rating is typically 25% of total system power • Improved efficiency due to reduced losses in the power electronic converter • Suitable for high power applications including recent advances in offshore installation • Allows converter to generator or absorb reactive power due to DFIG used • Control may be applied at a lower cost due to reduced converter power rating	• Increased control complexity due to increased number of switches in converter • Stator winding is directly connected to the grid and susceptible to grid disturbances • Increased capital cost and need for periodic slip ring maintenance • Increased slip ring sensitivity and maintenance in offshore installations • Is not direct drive and therefore requires a maintenance intensive gearbox for connection to wind turbine
Wound field synchronous generator	• Minimum mechanical wear due to slow machine rotation • Direct drive applicable further reducing cost since gearbox not needed • Allow for reactive power control as they are self excited machines that do not require reactive power injection • Readily accepted by electrically isolated systems for grid connection • Allow for independent control of both real and reactive power	• Typically have higher maintenance costs again in comparison to that of an IG • Magnet used which is necessary for synchronization is expensive • Magnet tends to become demagnetized while working in the powerful magnetic fields inside the generator • Requires synchronizing relay in order to properly synchronize with the grid

reactive power. As for the IG, they are relatively inexpensive and robust however, they require external excitation circuitry and reactive power from the grid. A main disadvantage is that they require a synchronizing relay for grid connection. The remainder of the disadvantage and advantages are listed in Table 2.

8. Conclusion

Wind energy generation has become a highly researched area. A concise review of various WECS has been achieved through this paper. Converter topologies used in combination with PMSG, DFIG, IG and SG, along with different control schemes has been described in detail. All control methods described, attempt to obtain maximum energy transfer from the wind turbine to the grid. There is a continuing effort to make converter and control schemes more efficient and cost effective in hopes of an economically viable solution to increasing environmental issues. Wind power generation has grown at an alarming rate in the past decade and will continue to do so as power electronic technology continues to advance.

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