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Dynamic Performance Analysis of a Grid-Connected Doubly-Fed Induction Generator

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Abstract: In the field of wind energy, the doubly fed induction generator (DFIG) is commonly used in variable speed wind energy conversion systems (WECS). This paper presents a review of various topologies, configurations, power converters and control schemes used with the operation of the DFIG. The operation of DFIG based on both slip ring and brushless arrangement has been discussed. The grid integration of DFIG and its influence on system stability, system reliability, power quality and power transmission is reviewed.
Index Terms: Doubly-fed induction generator, DFIG, wind energy conversion system, WECS, MPPT, grid operation.

I. INTRODUCTION

The Doubly-Fed Induction Generator (DFIG) is an induction generator with both stator and rotor windings. The DFIG is nowadays widely used in variable-speed wind energy applications with a static converter connected between the stator and rotor. Currently, this topology occupies close to 50% of the wind energy market. There are numerous pieces of literature [1-76] on the operation of WECSs based on DFIGs for the integration to the grid.

There is a deliberation on, the wind turbine generators in WECS [1-3], variable speed turbine [4-6] and various topology of DFIG which includes the brief description of slip ring induction generator and brushless doubly-fed induction generator [7-12]. Variable speed configuration of DFIG is elaborated in [13-15]. The various topologies of a power converter in DFIG along with their operation and application is discussed in [18-30]. The grid integration of DFIG influences various parameters such as system stability system reliability power quality power transmission.

This paper is intended to provide a comprehensive study about the DFIG which includes the aerodynamic, mechanical and electrical aspects of WECS, it is intended to cover the operation from variable speed turbine, power converter used, its integration into the utility system and thereafter also study the factors which are affected from its integration with the grid.

II. WIND ENERGY CONVERSION SYSTEM (WECS)

Greenhouse gas reduction has been one of the crucial and inevitable global challenges. The issue has come into focus especially in the last two decades as evidences on global warming have been reported. This has drawn increasing attention to renewable energies including wind energy [1]. WECS has an annual installation growth rate of 31.7% in 2009 with its growth rate is continuously increasing for the last few years. Wind energy is now one of the fastest-growing and attractive renewable energies [2]. The increasing price-competitiveness of wind energy against other conventional fossil fuel energy sources such as coal and natural gas is another positive [3]. WECS consists of three major aspects; aerodynamic, mechanical and electrical as shown in Figure 1. The electrical aspect of WECS can further be divided into three main components, which are wind turbine generators (WTGs), power electronic converters (PECs) and the utility grid.

A. Wind Turbine Generators

With consideration to its operating speed and the size of the associated converters, WTGs can be classified into three categories namely:
1) Fixed Speed Wind Turbine (FSWT)
2) Variable Speed Wind Turbine (VSWT) with partial scale frequency converter (PSFC)
3) Variable Speed Wind Turbine (VSWT) with full-scale frequency converter (FSFC)

FSWT including Squirrel-Cage Induction Generator (SCIG), led the market until 2003. The Doubly-Fed Induction Generator (DFIG), which is the main concept of VSWT with PSFC, overtook FSWT and has been leading WTG concept. It nearly has 85% of the market share [3].
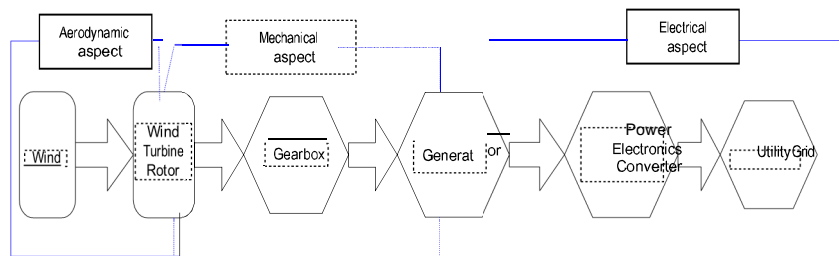
Fig.1 Wind Energy Conversion System (WECS)

B. Variable Speed Wind Turbines

The wind turbines may be of horizontal axis or vertical axis types. These turbines can be fixed speed and variable speed wind turbines. The fixed-speed wind turbines rotate at almost a constant speed, which is determined by the gear ratio, the grid frequency, and the number of poles of the generator. The maximum conversion efficiency can be achieved only at a given wind speed, and the system efficiency degrades at other wind speeds. The turbine is protected by aerodynamic control of the blades from possible damage caused by high wind gusts. The fixed-speed turbine generates highly fluctuating output power to the grid, causing disturbances to the power system. This type of turbine also requires a sturdy mechanical design to absorb high mechanical stresses [6].

On the other hand, variable-speed wind turbines can achieve maximum energy conversion efficiency over a wide range of wind speeds. The turbine can continuously adjust its rotational speed according to the wind speed. In doing so, the tip speed ratio, which is the ratio of the blade tip speed to the wind speed, can be kept at an optimal value to achieve the maximum power conversion efficiency at different wind speeds [4].

To make the turbine speed adjustable, the wind turbine generator is normally connected to the utility grid through a power converter system [5]. The converter system enables the control of the speed of the generator that is mechanically coupled to the rotor (blades) of the wind turbine. The main advantages of the variable-speed turbine include increased wind energy output, improved power quality, and reduced mechanical stress [6]. The main drawbacks are the increased manufacturing cost and power losses due to the use of power converters. Nevertheless, the additional cost and power losses are compensated for by the higher energy production.

Furthermore, the smoother operation provided by the controlled generator reduces mechanical stress on the turbine, the drive train and the supporting structure. This has enabled manufacturers to develop larger wind turbines that are more cost-effective. Due to the above reasons, variable-speed turbines dominate the present market.

III. TOPOLOGIES OF DFIG

The Doubly-fed induction generators are mostly utilized slip ring induction generators. Recently, brushless DFIG is also investigated.

A. Slip Ring Induction Generator

This topology is also called the DFIG. As shown in the figure.2, Its stator circuit is directly connected to the grid while the rotor circuit is connected to the grid via slip rings and a three-phase converter.

The DFIG is currently the system of choice for multi-MW wind turbines. The aerodynamic system must be capable of operating over a wide wind speed range to achieve optimum aerodynamic efficiency by tracking the optimum tip-speed ratio. Therefore, the generator's rotor must be able to operate at a variable rotational speed. The DFIG system, therefore, operates in both sub- and super-synchronous modes with a rotor speed range around the synchronous speed. For variable-speed systems where the speed range requirements are small, for example, ±30% of synchronous speed, the DFIG offers adequate performance and is sufficient for the speed range required to exploit typical wind resources.

An AC-DC-AC converter is included in the induction generator rotor circuit. The power electronic converters need only be rated to handle a fraction of the total power – the rotor power – typically about 30% nominal generator power. Therefore, the losses in the power electronic converter can be reduced, compared to a system where the converter has to handle the entire power, and the system cost is lower due to the partially-rated power electronics. Here we will introduce the basic features and normal operation of DFIG systems for wind power applications basing the description on the standard induction generator. Different aspects that will be described include their variable-speed feature, power converters and their associated control systems, and application issues.
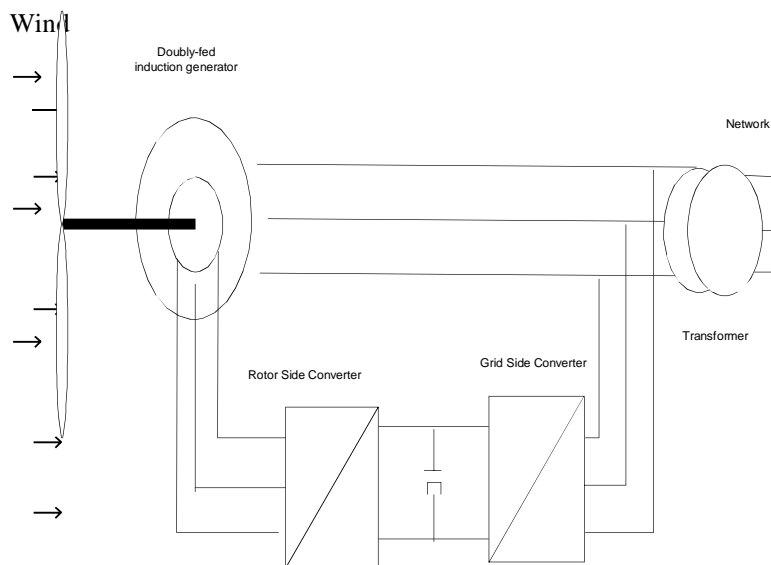
Fig. 2 Doubly-fed induction generator

Figure.3. shows mechanical power 'Pm' versus slip, 's' characteristics of a DFIG wind energy system. The negative value of mechanical power indicates that the DFIG is in the generating mode. Since the rotor speed of the DFIG is adjustable, by using the maximum power point tracking (MPPT) schemes can be implemented to harvest the maximum available power from the wind turbine. When operating at the maximum power point (MPP) on the turbine power-speed curves, the generator's mechanical power from the shaft 'Pm' is proportional to the cube of the rotor speed 'ω_r'.

The rotor speed is varying in the range of 0.5 ω_s to l.2 ω_s. This speed range is normally sufficient for a wind energy system since the power generated at 42% of the rated speed is 7.4% of the rated power. Dynamically, the DFIG may operate at 30% above the synchronous speed. As a consequence, the power converters in the rotor circuit should be designed to handle about 30% of the rated stator power.
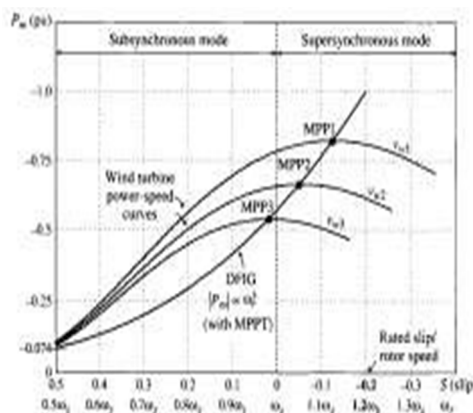

Fig.3 Power-Speed characteristics in a DFIG wind energy system with MPPT control.

Depending on the rotor speed, there are two modes of operation in a DFIG WECS [7]; namely super-synchronous mode, sub-synchronous mode. The slip is negative in the super-synchronous mode and becomes positive in the sub-synchronous mode.

Figure 4 and Figure 5, show the power flow in a DFIG during super-synchronous & sub-synchronous mode of operation. Depending on whether the slip is positive or negative, the rotor circuit can receive or deliver power from or to the grid. In the super-synchronous operation mode, the mechanical power $|P_m|$ from the shaft is delivered to the grid through both stator and rotor circuits. The rotor power $|P_r|$ is transferred to the grid by power converters in the rotor circuit, whereas the stator power $|P_s|$ is delivered to the grid directly. Neglecting the losses in the generator and converters, the power delivered to the grid $|P_g|$ is the mechanical power $|P_m|$ of the generator, as illustrated in Figure 4.
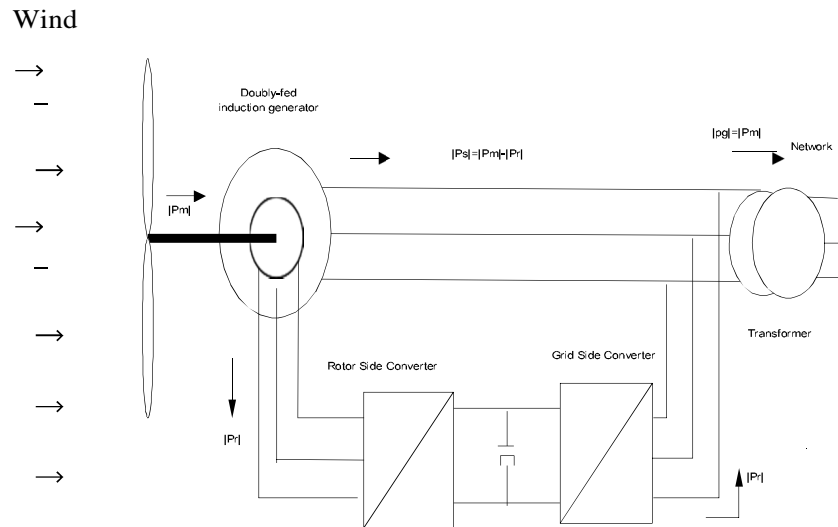
Fig 4. Power flow in DFIG WECS under the super-synchronous mode of operation

For the sub-synchronous operation in Figure 5, the rotor receives the power from the grid. Both mechanical power $|P_m|$ and rotor power $|P_r|$ are delivered to the grid through the stator. Although the stator power $|P_S|$ is the sum of $|P_m|$ and $|P_r|$, it will not exceed its power rating since in the sub-synchronous mode the mechanical power $|P_m|$ from the generator shaft is lower than that in the super-synchronous mode. As in the previous case, neglecting the losses, the total power delivered to the grid $|P_g|$ is the input mechanical power $|P_m|$.

Since the DFIG generates high power when operating in the super-synchronous mode, the power rating for the converter is determined by the rated or maximum slip in the super-synchronous mode.
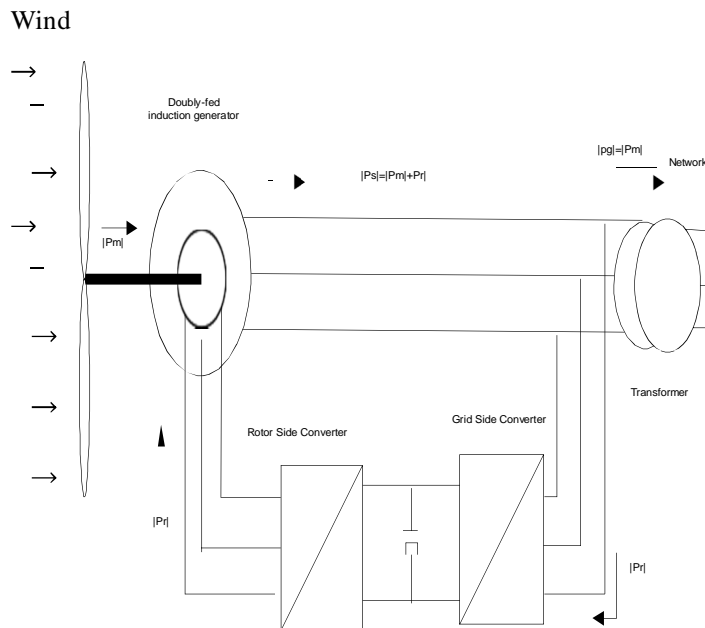
Fig.5 Power flow in DFIG WECS under the sub-synchronous mode of operation

B.   Brushless Doubly –Fed Induction Generator (BDFIG)

The most significant features of the Brushless DFIG are that a) it is brushless in operation, b) it utilizes a fractionally rated converter, and c) it shows greater compatibility with grid codes than the conventional DFIG, thereby providing substantial economic benefits. The Brushless DFIG is particularly attractive as an alternative replacement for doubly-fed slip-ring induction generators (DFIGs) in wind power plants, as brushless operation reduces the maintenance requirements and increases reliability. These advantages will become even more significant as more wind turbines are built offshore. The brushless doubly-fed machine can also be used as a motor in variable speed drive applications, making it the ideal choice in pumping, as well as many other applications.

The contemporary BDFIG is a single frame induction machine, without any brushes, it has two 3-phase stator windings of different pole numbers. Typically the two stator supplies are of different frequencies, one a fixed frequency supply connected to the grid, and the other a variable frequency supply derived from a power electronic frequency converter, as illustrated in Fig. 6.
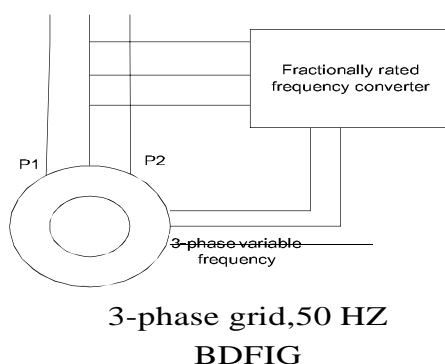

Fig.6 Brushless doubly-fed induction machine connected to the grid

The BDFIG may be thought of as the combination of two induction machines, of different stator poles, these machines will have different synchronous speeds, for the same supply frequency. With their rotors connected both physically and electrically. Physically this machine is very similar to the self-cascaded machine proposed by Hunt [10], the main distinction is that the BDFIG is explicitly a doubly-fed machine. This combination of induction machines is similar to the traditional cascade connection of induction machines. In a traditional cascade connection, the rotor of one machine was connected to the stator of the other via slip rings. However, it was Hunt [10] who realized that if both machines were in the same frame, then the rotor can be connected using slip rings [10]. It can be operated in an asynchronous or synchronous mode of operation. During the asynchronous mode of operation, the shaft speed is dependent on the loading of the generator, as well as the supply frequency. If stator 1 has p_1 pole pairs, and stator 2 p_2 pole pairs, then the BDFIG can be operated as an induction generator of either p_1 pole pairs or p_2 pole pairs, by connecting stator 1 or stator 2 respectively, and leaving the other supply unconnected in each case. In the sequel this mode of operation will be referred to as simple induction mode. The characteristics of the BDFIG in this mode are the same as those of a standard induction generator, except that the performance will be poor.
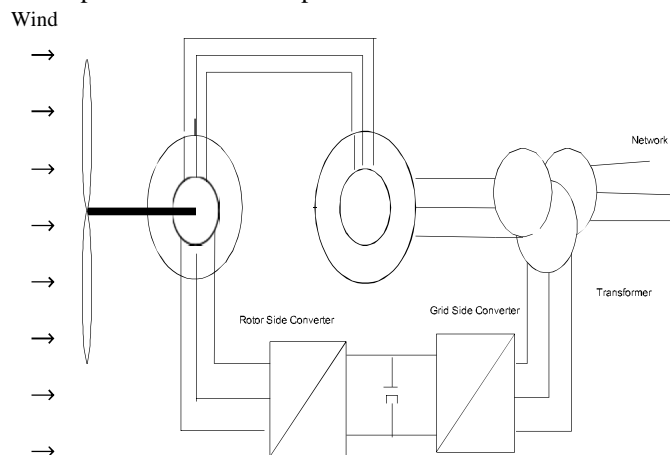

Fig.7 Brushless Doubly-fed induction generator

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However, if the non-supplied stator winding is short-circuited, then the behaviour of the generator is like that of a cascaded induction generator. A cascade induction generator formed from p_1 and p_2 pole pair induction generator has characteristics that resemble an induction generator with $p_1 + p_2$ pole pairs and this mode will be referred to as cascade induction mode.

The design of the machine is to be optimized for an asynchronous mode of operation. The synchronous mode of operation of the BDFIG relies on *cross-coupling* between the stator and rotor [12], of operation.

Cross-coupling means the coupling of the field produced by stator 1 to stator 2, and vice-versa.

If stator 1 has p_1 pole pairs and is supplied with a three-phase supply at ω_1 rad/s, then the stator current wave, and hence air gap magnetic flux density will rotate at ω_1/p_1 rad/s. Similarly, if stator 2 has p_2 pole pairs and rotates at ω_2 rad/s then the waveforms will rotate at ω_2/p_2 rad/s.

If the rotor is rotating at ω_r rad/s, then the magnetic flux densities, in the rotor reference frame, are travelling waves of frequency $(\omega_1-\omega_r p_1)$ and $(\omega_2-\omega_r p_2)$ respectively. Therefore if a constant torque is to be produced by cross-coupling then $(\omega_1-\omega_r p_1) = \pm(\omega_2 - \omega_r p_2)$. Taking the negative condition and rearranging gives:

$$\omega_r = \frac{\omega_1 + \omega_2}{p_1 + p_2}$$

The above equation gives the requirement on rotor speed for cross-coupling to occur in steady-state. When second supply is fed from D.C., $\omega_2=0$,

$$\omega_r = \frac{\omega_1}{p_1 + p_2}$$

It is regarded as natural speed and this operating condition has been noted by Broadway & Burbridge [9].

Furthermore, it can be shown that the power factor of the machine can be controlled in this synchronous mode, and, subject to inverter capacity, the grid-connected winding may run at the leading power factor [12].

IV. VARIABLE SPEED CONFIGURATION OFDFIG

The configuration of this system is the same as that of the WRIG system except for that (1) the variable resistance in the rotor circuit is replaced by a grid-connected power converter system, and (2) there is no need for the soft starter or reactive power compensation. The power factor of the system can be adjusted by the power converters. The converters only have to process the slip power in the rotor circuits, which is approximately 30% of the rated power of the generator, resulting in reduced converter cost in comparison to the wind energy systems using full-capacity converters [15]. The use of the converters also allows bidirectional power flow in the rotor circuit and increases the speed range of the generator. This system features improved overall power conversion efficiency, extended generator speed range (±30%), and enhanced dynamic performance as compared to the fixed-speed WECS and the variable resistance configuration. These features have made the DFIG wind energy system widely accepted in today's market.

The variable-speed DFIG wind energy system is one of the main WECS configurations in today's wind power industry. As shown in Figure 2, the stator is connected to the grid directly, whereas the rotor is connected to the grid via reduced-capacity power converters [13]. A two-level IGBT voltage source converter (VSC) system in a back-to-back configuration is normally used. Since both stator and rotor can feed energy to the grid, the generator is known as a doubly-fed generator.

The rotor-side converter (RSC) controls the torque or active/reactive power of the generator while the grid-side converter (GSC) controls the DC-link voltage and its AC-side reactive power. Since the system can control the reactive power, external reactive power compensation is not needed.

V. POWER CONVERTER TOPOLOGY FORDFIG

The doubly-fed induction generator (DFIG) has received much attention in wind energy conversion. If a wound rotor induction machine (DFIG) 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 can 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, the converter power rating is reduced since it is connected to the rotor, whilst the majority of the power flows through the stator.

A. 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 [16], Fig. 8. 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 operating point of maximum power transfer [16]. 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) [17, 18].
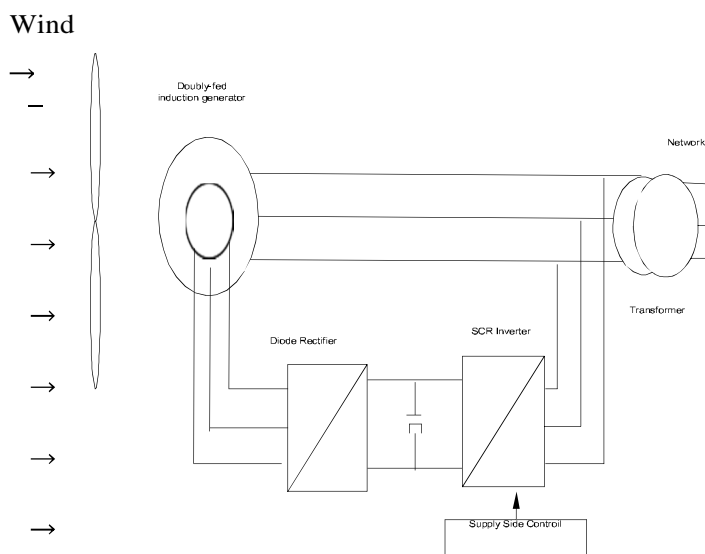

Fig .8 DFIG with Static Cramer drive

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 gearbox, to its optimum value [17]. 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 [18]. 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 the greatest power transfer. It is discovered that between 7.5 and 8.5m/s, maximum power can be generated in both sub- and super-synchronous modes [18]. 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.

Watthana and Bunlung studied the sliding mode control of wind turbines utilizing DFIG by using cramers drive in converter topology.

B. Back-to-Back PWM Converters

A more technologically advanced method using back-to-back converters has been developed, Fig. 10. Much work has been presented using this type of converter [19-24]. 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 [19, 20]. 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 [19, 20]. As for the rotor side, the choice of decoupled control of the electrical torque and the rotor excitation current is presented [19]. 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 [20], the rotor current was decomposed into d-q 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 [19], or alternatively space vector modulation (SVM) is used to achieve a better modulation index in [20].

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 [21, 22]. 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 [21]. 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 to control the real and reactive power of the machine. Another different option for rotor control has been identified [22]. 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 the dynamics of the speed controller are not extremely fast, else large transients in generator torque may occur [22].

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 sectors the controller is operating in. From the choice of the sector, the applied voltage vectors can be determined from another table. The controller tables and details are provided in [23].
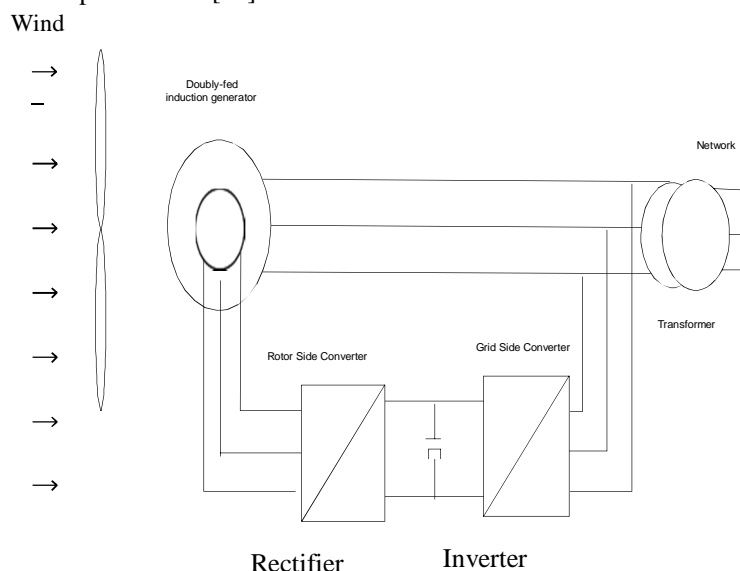

Fig.9 DFIG with back–to–back converters

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 [24]. 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 [24]. The design of DFIG using a back-to-back PWM converter is given in [25-30]. The analysis of decoupled d-q vector control scheme is implemented in [25-28]for the independent control of active, reactive power and to provide wide speed operation by using a back-to-back PWM converter connected between the rotor side and the utility grid. The converter performance of grid-connected wind energy conversion system is analyzed in [29] for DFIG with back-to-back PWM. Since PWM generates harmonics, so to overcome this harmonics filters are required [30] to design the LCL filters for the back-to-back PWM converter in DFIG.

C. 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. 10. 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. 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, whereas the q-axis current helps regulate the stator-side active power [14].
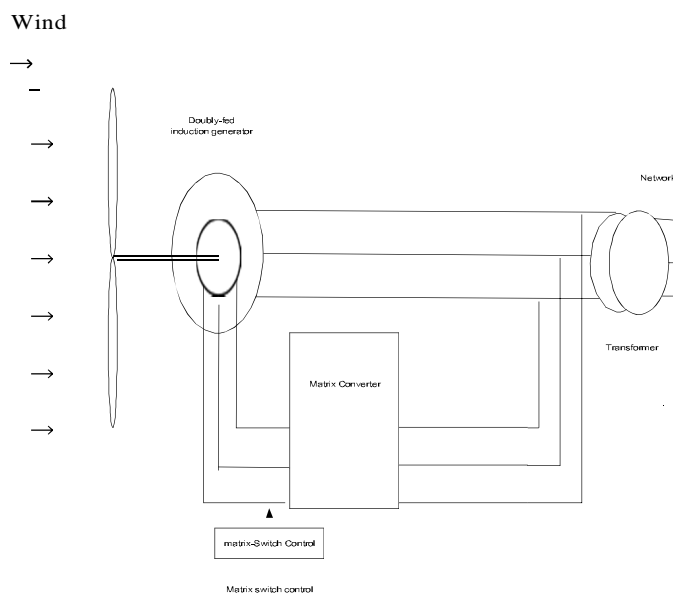
Wind

Fig.10 DFIG with Matrix Converter

Another option is to control the rotor winding voltage, which consequently manipulates the power factor of the DFIG [22]. The matrix converter consists of nine bidirectional switches (18 total), arranged in a manner such that any input phase may be connected to any output phase at any time. Each 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 [30]. One of the major drawbacks of a matrix converter is that 18 total switches are required, causing an increase in converter semiconductor cost.

The grid-connected wind-power generation scheme using DFIG in conjunction with a direct AC-AC matrix converter is proposed in it employs an SFO vector control algorithm, it highlights the matrix converter based rotor current control scheme. The performance of grid-connected WECS based on DFIG fed by matrix converter is proposed in [19]. A simple and easy modulation scheme called DDPWM is proposed in to confirm the reliable application of matrix converter for the DFIG. Presents a control strategy for a DFIG using an indirect matrix converter. The control of terminal voltage and frequency along with the power factor at the interface with the grid using matrix [18].

VI. CONTROL SYSTEM FOR DFIG

A. Maximum Power Point Tracking (MPPT) Control

The control of a variable-speed wind turbine below the rated wind speed is achieved by controlling the generator. The main goal is to maximize the wind power capture at different wind speeds, which can be achieved by adjusting the turbine speed in such a way that the optimal tip speed ratio λ_{opt} is maintained.

Figure 11. shows the typical characteristics of a wind turbine operating at different wind speeds, where Pm and ωm are the mechanical power and mechanical speed of the turbine, respectively. The Pm versus ωm curves is obtained with the blade angle of attack set to its optimal value. For the convenience of analysis and discussion, the mechanical power, turbine speed, and wind speed are all expressed in per-unit terms.

For a given wind speed, each power curve has a maximum power point (MPP) at which the optimal tip speed ratio λopt is achieved. To obtain the maximum available power from the wind at different wind speeds, the turbine speed must be adjusted to ensure its operation at all the MPPs. The trajectory of MPPs represents a power curve, which can be described by

$$P_m \propto \omega_m$$

The mechanical power captured by the turbine can also be expressed in terms of the torque:

$$P_m \propto T_m \omega_m$$

Where Tm is the turbine mechanical torque. From the above two equations:

$$T_m \propto \omega_m^2$$

The relations between the mechanical power, speed, and torque of a wind turbine can be used to determine the optimal speed or torque reference to control the generator and achieve the MPP operation. Several control schemes have been developed to perform the maximum power point tracking (MPPT), and a brief description of three MPPT methods is given in the next subsections.

According to the power curve illustrated in Figure.11, the operation of the wind turbine can be divided into three modes: parking mode, generator-control mode, and pitch-control mode:

1) *Parking Mode:* When the wind speed is below cut-in speed, the turbine system generates less power than its internal consumption and, therefore, the turbine is kept in parking mode. The blades are completely pitched out of the wind, and the mechanical brake is on.
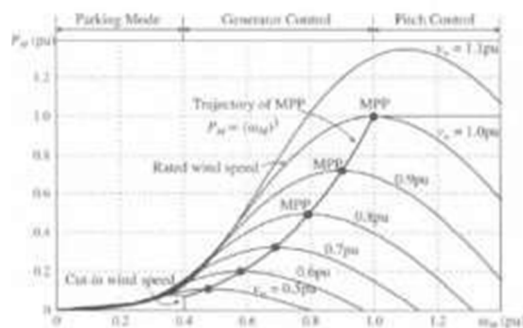

Fig.11 characteristics of wind turbine operating at different wind speeds

2) *Generator-control Mode:* When the wind speed is between the cut-in and rated speed, the blades are pitched into the wind with its optimal angle of attack. The turbine operates with variable rotational speeds to track the MPP at different wind speeds. This is achieved by the proper control of the generator.

3) *Pitch-control Mode:* For higher than rated wind speeds but below the cut-out limit, the captured power is kept constant by the pitch mechanism to protect the turbine from damage while the system generates and delivers the rated power to the grid. The blades are pitched out of the wind gradually with the wind speed, and the generator speed is controlled accordingly. When the wind speed reaches or exceeds the cut-out speed, the blades are pitched completely out of the wind. No power is captured, and turbine speed is reduced to zero. The turbine will be locked into the parking mode to prevent damage from the strong wind.

B. Rotor-Side Converter Control

The rotor-side converter (RSC) provides the excitation for the induction machine rotor. With this PWM converter, it is possible to control the torque hence the speed of the DFIG and also the power factor at the stator terminals. The rotor-side converter provides a varying excitation frequency depending on the wind speed conditions. The function of the receiving end converter is to feed in the active power transmitted by the sending end converter while maintaining the DC voltage at the desired level. Additionally, the reactive power channel can be used to support the grid voltage during faults and also in steady-state. The PI- controller maintains DC voltage through active converter current under consideration of a feed-forward term representing the power transfer through the DC link. AC voltage control is performed by two PI controllers. The controller in the upper branch is slow and only responsible for set-point tracing in steady-state operation. The second controller is very fast and is activated during grid faults. The magnitude of the current outputs is limited. In steady-state operation, the DC voltage control has a higher priority.

C. Grid-Side Converter Control

The grid-side converter controls the flow of real and reactive power to the grid, through the grid interfacing inductance. The objective of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The sending end converter is responsible for transmitting the active power produced by the wind farm while maintaining the AC voltage in the wind farm grid. Furthermore, it can be used for frequency control which in turn controls the changes in the generator slip of the connected DFIG wind turbines. Thus, active power transfer through the low-rated converter in the rotor circuit of the DFIG can be limited without a reduction of total Power. As the power control is performed by the wind turbines, a simple voltage magnitude controller can be used for the sending end converter, thus fulfilling the aforementioned requirements. The frequency can be directly regulated without the need for a closed-loop structure.

VII. GRID INTEGRATION OF DOUBLY-FED INDUCTION GENERATOR

In the grid integration of DFIG, the Stator windings are directly connected to the grid and the wound rotor is connected to the grid via two back-to-back voltage source inverters. The grid side converter is connected via three chokes to filter the current harmonics. Hence rotor currents can be controlled with a wished frequency and the power quality of grid currents can be guaranteed. The operation influences system stability, system reliability, power quality and power transmission.

A. System Stability

According to the classification of power system stability in reference, power system stability could be categorized into voltage stability, frequency stability and rotor angle stability. VSWTSs have the ability to control reactive power and decouple active and reactive power control through electronic converters. Thus, the voltage stability of power systems is improved. Besides that wind energy could be restored as rotating kinetic energy in blade and hub, and then released by DFIG if necessary.

So the frequency stability of grids could be enhanced temporarily.

1) *Stability Model:* Different types of reduced-order stability models for DFIGs are discussed and compared in the study [24].

2) *Voltage Stability:* The voltage support could be provided by DFIG to enhance the voltage stability of grids. Besides that, the fault-ride through capability for DFIG is also required by system grid codes to improve the voltage stability during the large disturbance. Both of the influences mentioned above are discussed in studies. In the study, a reactive power control scheme is proposed for voltage regulation at a remote location with taking into account its operating state and limits. The study derives a steady-state PQ diagram for a DFIG and concluded the reactive power production limitation is the rotor current limit. That conclusion is crucial for voltage stability evaluation. Considering the DFIG is quite sensitive to grid fault, the study designs a voltage control scheme to coordinate the rotor-side and grid-side converter. A field-test unit is introduced in the study, which could generate a voltage dip at the WT terminals. Researches in studies present modelling, analysis and control design of DFIG-based Wind turbines under unbalanced network conditions.

3) *Frequency Stability:* Studies [4] – [5] discuss the effect on frequency stability by grid-connected wind farms with VSWTSs. A control scheme that allows DFIGs to participate effectively in system frequency regulation is proposed in the study [10]. A controller is designed in the study [2], which helps to reduce the frequency drop following the transient period after the loss of network generation.

4) *Rotor Angle Stability:* Only a few research works have been published on the rotor angle stability area because there is still no exact and accepted rotor angle concept for variable speed generators especially DFIG. The study proposes a control scheme for DFIG named after "Rotor Flux Magnitude and Angle" (FMAC) which defines the angle between the rotor flux vector and the d-axis of the reference frame as rotor angle. In the study, a power system stabilizer (PSS) is designed accord to the rotor angle concept mentioned above.

B. System Reliability

It is necessary and important to analyze grid reliability due to the wind power fluctuation before a wind farm is built. Studies are concern with the modelling, algorithm and evaluation method of reliability. Studies develop a simplified wind power generation model for DFIGs which contains a six-step wind speed model applicable to multiple geographic locations and adequate for reliability evaluation of power. This model can be used in the conventional generating system adequacy assessment utilizing analytical or Monte Carlo state-sampling techniques. The research compares representative population-based intelligent search algorithms with traditional Monte Carlo simulation methodology on power systems reliability assessment with wind power fluctuation.

C. Power Quality

Power fluctuation caused by a large penetration of wind generation will influence on power quality such as voltage flicker, frequency deviation significantly. Meanwhile the harmonics current sourced from control system also increases the THD (Total Harmonic Distortion) index of power systems. Several studies focus on these topics as below:

1) *Voltage flicker:* During the continuous operation and switching operation, wind turbine causes voltage flicker. Studies evaluate the flicker effect by wind farm. In study [8], the calculation of maximum apparent power and flicker of residential and commercial radial distribution feeder with remotely connected wind turbines has been investigated. The flicker emission of variable speed wind turbines with DFIGs is investigated by study [9], and the dependence of flicker emission on mean wind speed, wind turbulence intensity, short circuit capacity of grids and grid impedance angle are analyzed. Furthermore a comparison on the flicker is also done with the fixed speed wind turbine in this paper. In study [20], a simplified second-order model for prediction of the response of DFIG wind turbines is derived and using this model steady-state impact, such as flicker emission is measured and analyzed.

2) *Frequency Deviation:* The frequency deviation caused by power fluctuation for a long term is just inevitable. Studies discuss on this problem. In study, the frequency deviation is estimated by a deterministic method based on the transfer functions of system components. In study a scheme for supervisory control of wind farms is presented, which concentrates on reduction of power output variation. Study presents a method to quantify wind penetration based on the amount of fluctuating wind power that can be filtered by wind turbine generators.

3) *Harmonic Emission:* Variable speed turbines are equipped with power electronic systems, which are mainly PWM inverters, using insulated gate bipolar transistor (IGBT) technology. The PWM inverter is convenient to implement control strategies; however, the disadvantages are that harmonic currents are produced. Studies discuss the effect of the harmonic current injected. In the study, important general characteristics of the harmonic behaviour of WTs are outlined. The study analyzes the repercussions of the connection of wind farms with variable speed generators on the operation of weak electric distribution systems.

D. Wind Power Transmission

With the wind being an uncontrollable resource, power delivery from a large-scale wind farm into a power system poses challenges. Studies [17]-[13] further discuss this topic. Studies [28] and [29] consider a solution for integration of large offshore doubly fed induction generator-based wind farms with a common collection bus controlled by a STATCOM into the main onshore grid using the line-commutated high-voltage dc connection. Studies [10] and [11] describe the use of voltage source converter (VSC)-based HVDC transmission system (VSC transmission) technology for connecting large DFIG-based wind farms over a long distance. In a study [12], the impact of a static synchronous compensator (STATCOM) to facilitate the integration of a large wind farm (WF) into a weak power system is studied. Study [13] concerns with the issue of the fault ride-through capability of a wind farm of induction generators, which is connected to an AC grid through an HVDC link based on voltage sourced converters (VSCs).

VIII. CONCLUSION

In this paper, the detailed study of DFIG along with its topology, grid configuration, relevant power converter devices, appropriate control parameters, integration with the utility grid and its effect on the various system conditions are presented. The operation of both slip ring and brushless arrangement of DFIG has been summarized. The influence of DFIG on the performance, system stability, system reliability, power quality and power transmission has been reviewed. This comprehensive review will be helpful for researchers working in the area of DFIG.

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