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Study the Types of Electrical Generators Used in Wind Turbines

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Abstract

Generation of electricity from renewable sources has grown substantially owing to active governmental stimulation programs in many countries. Wind energy is considered one of the most efficient types of renewable energy. In wind turbines there are many types of generators can be used. This article presents a comparative analysis of all types of electrical generators that are used in wind energy in addition to determining advantages and disadvantages for it. Synchronous generators can be a good choice for variable speed operation since it has low rotational synchronous speed that produces the voltage at grid frequency. Permanent magnet synchronous generators (PMSG) do not require gearbox but PMSG has a big size so it can be a suitable selection for small wind turbines. Squirrel cage induction generators (SCIG) suitable for variable speed operations since grid is absolutely decoupled. One of disadvantage of SCIG is that gears are unavoidable. Doubly fed induction generators (DFIG) Compared with the earlier generator type it is simpler in mechanical design and electrical structure, but gearboxes and brushes are still essential. To overcome disadvantages of DFIG, Brushless Doubly fed induction generators (BDFIG) be consider as a wise decision because of the power of bidirectional converter is low in BDFIG, in addition to absence of brushes which reduces needing for periodic maintenance operations, Moreover, better investment for the wind turbine. This research has studied modes of operation for induction machines. Finally, advantages and disadvantages for each type of generators are summarized.

Keywords: Asynchronous Generator, Brushless Doubly Fed Induction Generator, Doubly Fed Induction Generator, Synchronous Generator

Rüzgâr Türbinlerinde Kullanılan Elektrik Jeneratörlerinin Türlerini

Özet

Birçok ülkedeki aktif hükümet teşvik programları sayesinde yenilenebilir kaynaklardan elektrik üretimi önemli ölçüde arttır. Rüzgâr enerjisi, yenilenebilir enerjinin en verimli türlerinden biri olarak kabul edilir. Rüzgâr türbinlerinde çok çeşitli jeneratör tipleri kullanılabilir. Bu makale, rüzgâr enerjisinde kullanılan tüm elektrik jeneratörlerinin karşılaştırmalı bir analizini sunarak, bunun avantajlarını ve dezavantajlarını belirlemektedir. Senkron jeneratörler, şebeke frekansında gerilim üreten düşük dönme senkron hızına sahip oldukları için değişken hızlı çalışma için iyi bir seçim olabilir. Kalıcı mıknatıslı senkron jeneratörler (PMSG) dişli kutusuna ihtiyaç duymazlar ancak PMSG büyük boyutlu olduğundan küçük rüzgâr türbinleri için uygun bir seçim olabilir. Şebeke tamamen ayrı olduğundan, değişken hızlı işlemler için uygun sincap kafesli endüksiyon jeneratörleri (SCIG). SCIG'lerin dezavantajlarından biri dişlilerin kaçınılmaz olmasıdır. Çift beslemeli endüksiyon jeneratörleri (DFIG) Önceki jeneratör tiplerine kıyasla mekanik tasarım ve elektriksel yapı olarak daha basittir, ancak dişli kutuları ve fırçalar hala gereklidir. DFIG'nin dezavantajlarını aşmak için, Fırçasız Çift Beslemeli Endüksiyon

Jeneratörleri (BDFIG) akıllıca bir karar olarak düşünülebilir, çünkü BDFIG'de çift yönlü dönüştürücünün gücü düşüktür, ayrıca fırçaların olmaması periyodik bakım operasyonlarına olan ihtiyacı azaltır, ayrıca rüzgâr türbini için daha iyi bir yatırımdır. Bu araştırmada, endüksiyon makinelerinin çalışma modları incelenmiştir. Son olarak, her jeneratör tipinin avantajları ve dezavantajları özetlenmiştir.

Anahtar Kelimeler: Asenkron Jeneratör, Fırçasız Çift Beslemeli Asenkron Jeneratörü, Çift Beslemeli Asenkron Jeneratörü, Senkron Jeneratör

1. INTRODUCTION

In addition to satisfying consumer demand for electricity, using of renewable energy sources like wind energy-solar energy for generation of electricity is becoming more and more important in the fight against environmental degradation and global warming [1]. wind energy conversion systems are being installed in considerable quantities due to their clean and cost-effective energy conversion [2-3].

Wind turbine research and development has, since its inception, focused mainly on the design of generators. The electrical generator is the most important component of wind power generation system [4], as it is in charge of converting the wind's kinetic energy into electrical energy. The more successful of choosing the type of electrical generator that connected to wind turbine, means the more of reducing the amount of losses and thus leads to obtain a higher efficiency and produce electrical energy.

Both fixed and variable speeds are possible for wind turbines. The generator's stator in a fixed speed wind turbine is connected to the grid directly. On the other hand, for variable-speed wind turbine, a power electronic converter controls in machine, it is located between the machine and the grid converter [2].

Several of generator types are suitable for use in wind turbines, each has its own advantages and disadvantages. In this chapter, review of the types of electrical generators most commonly used in wind turbines has been presented, in addition to simplified technical comparison between them has been presented to ascertain the benefits and drawbacks of every one of them.

2. SYNCHRONOUS GENERATORS

Synchronous generator typically consists of a rotor that generates magnetic field and a stator that houses a set of three-phase windings that supply the external load. A direct current (flowing in a wound field or a permanent magnetic field) can supply power to the rotor. As a result of the flux generation, the synchronous speed specified in equation (1) is always equal to the frequency of the voltage that is induced in the stator winding [5].

$$\omega_{sync} = \frac{120.f}{p} \tag{1}$$

f is the frequency; p is the number of pairs of poles [6].

the name synchronous machine, is due to their design and synchronous operation. Compared to induction generators, synchronous generators are more appropriate for direct drive applications. these machines' rotors have been based on electromagnetic poles for many years, because they are comparatively inexpensive and resistant to demagnetization. However, new technologies are extending the life of permanent magnets, reducing the size of rotors, and doing away with the requirement for DC current in order to magnetize rotors. With more poles, a more durable direct drive wind turbine based on permanent magnet synchronous generators (PMSG) are produced [5].

There are many topologies of PMSG are being studied by researchers and employed in the industry at the moment. As their names imply, these generators are oriented by the magnetic field which is generated inside the machine and have different advantages that can be utilized in different situations. Synchronous generators distinguished by the direction of magnetic field that is generated in the machine and offer various benefits that can be applied in various situations. The axial-flux synchronous machines seem to have more advantages in terms of reduced size and better power-to-weight ratio, but more research is needed to determine whether or not these machines are suitable for high-power operation [5].

The elimination of the gearbox is the main advantage of synchronous generators in wind power, whatever the topology, in addition to the ability to deliver reactive power to the grid. With the power converter included, there is a cost to this. This requirement stems from the basic fact that the generators' voltage and frequency depend solely on the turbine's pitch and speed of wind. Therefore, in order to achieve appropriate output frequency regulation, it is essential to install a power converter unit between the generator and the grid. A configuration of a synchronous generator that used with wind turbine has shown in figure 1. in this case, the inverter must be designed to handle the generator's maximum power, that increasing the system's overall cost and size [5].

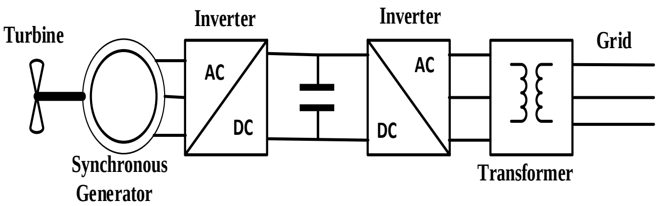

Figure 1. Synchronous generators with an indirect grid connection.

The synchronous generator can operate independently of the grid or be connected to the grid, but it constantly requires DC current for excitation, this is one of the drawbacks of the generator. It has the advantage of being connected to the electrical grid directly to operate at a fixed synchronous speed, and this requires stabilizing their rotational speed by controlling their deflection angles, but this leads to losing a larger portion of the wind energy. The problems of the synchronous generator, such as consuming DC current, operating at a fixed speed, and the problems of synchronization with the grid, were largely solved by connecting the generator to the grid via electronic drive elements.

Mathematical model for synchronous machines in stator reference frames can be written as:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = R_s \begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} + \begin{bmatrix} L_q & 0 \\ 0 & L_d \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} + \lambda_{af}\omega_r \begin{bmatrix} \cos\theta_r \\ -\sin\theta_r \end{bmatrix} \tag{2}$$

V_{qs} , V_{ds} : the stator voltages in the q- and d-axes (V).

I_{qs} , I_{ds} : the stator currents in q- and d-axes(A).

R_s: stator resistance (Ω).

L_d, L_q : self- and mutual inductances in d- and q-axes (H).

λ_{af} : rotor flux linkage (Wb)

ω_r : electrical angular rotor speed (rad/sec).

θ_r : electrical angle of rotor (rad).

$$\frac{d\omega_m}{dt} = \frac{1}{J}[T_e - T_l - B.\omega_m] \quad (3)$$

B : friction coefficient (N·m·s/rad).

J : inertia of motor(kg·m²).

ω_m : mechanical angular rotor speed (rad/sec).

T_e , T_l : electromagnetic , load torque(N.m).

2.1. Wound Field Synchronous Generators (WFSG)

The winding of stator is connected to grid through a bidirectional power converter. The grid side converter controls the reactive and active power which is delivered by the wind power system to the customers, while the machine side converter controls the torque [2]. Among the benefits of the Wound Field Synchronous Generator are:

1. This machine often has a high efficiency because it produces electromagnetic torque by using the whole stator current[7].

2. The main advantage of using a salient pole wound field synchronous generator is ability to directly control the machine's power factor and, as a result, decrease the stator current under all operating conditions [2].

We can conclude that a permanent magnets synchronous generator is superior to a wound field synchronous generator based on our comparison. Furthermore, the converter must be at least 1.3 times the nominal power of wind power system in order to regulate the amount of active and reactive power produced.

2.2 Permanent Magnet Synchronous Generator (PMSG)

Many configuration schemes that generate power utilizing a synchronous generator with a permanent magnet have been implemented [8]. In one of them, a three-phase rectifier, boost converter, and synchronous generator with permanent magnet were connected. In this case, electromagnetic torque is controlled by the boost converter. The use of a diode rectifier is one disadvantage of this configuration. As a result, for small-scale wind power systems (WPS) under 50 kW, this configuration has been considered.

The rectifier is positioned between the DC link and the generator and connects a second inverter to the grid in an alternative PMSG scheme. To decrease losses in the power electronic circuit and generator, applying of field orientation control (FOC) has benefit of allowing the generator to operate close to its optimal operating point. Although, the performance is reliant on the good understanding of generator parameter that varies with frequency and temperature. The main drawbacks of using PMSG are the high cost of permanent magnets, which increases machine costs, the demagnetization of permanent magnet material, and the inability to control the machine's power factor [9-11].

3. ASYNCHRONOUS GENERATORS

The induction generator is a kind of AC generator which has been utilized with wind turbines. Wind turbines can be used with many kinds of induction generators such as: wound rotor, doubly fed, brushless doubly fed and squirrel cage induction generators. The majority of recently constructed wind turbines have used induction generators for several reasons, such as Lower cost[12], Robustness, The availability of generators for every capacity on the market, Flexibility in speed features, Maturity of technologies that are used in designing and manufacturing generators.

A squirrel-cage induction generator does not require slip rings as in a wound-rotor induction generator or a synchronous generator. Regarding the wound-circuit induction generator, it has slip rings that are connected to a group of resistors or a two-way thyristor switch to control the current of rotor [13-14].

The induction generator does not need a DC source to feed its poles, as it draws the necessary supply current from the grid to which it is connected. On the other hand, if the induction generator operates independently with the grid, it has been fed through a group of capacitors connected to the terminals of the stator to supply it with the reactive power necessary to generate the magnetizing current which produces magnetic flux, the induction generator is also characterized by the lack of auxiliary devices compared to the synchronous generator. Also, operating it in parallel with the grid can be done at any frequency without achieving the synchronization conditions that synchronous generators must fulfill, so that when connecting induction generators in parallel, the rotation of the rotor must be at a speed close to the synchronous speed and in the same direction as the magnetic flux, noting that when connecting them, it shows the phenomena that occur when connecting transformers or induction motors.

The biggest drawback of induction generators is their high magnetization current. Since the magnetization current in the induction machine is (25÷50) % of the nominal current of the machine, therefore, when a constant voltage is available to grid, reactive power that is required for excitation is (25÷50) % of the generated power, in addition to the other power losses in the generator, which makes the efficiency of induction generators are low compared to synchronous generators. On the other hand, the magnetizing current lags voltage by an angle of 90°, and thus the operation of induction generators in parallel with synchronous generators leads to a decrease in the value of $\cos\theta$ for these generators, even if the external load is a purely ohmic load.

3.1 Squirrel Cage Induction Generator (SCIG)

Three-phase squirrel cage induction generators are typically used with stand-alone wind power systems which use wind and hydropower and other renewable energy sources. An induction machine can operate as a self-excited induction generator if its rotor is operated externally at a suitable speed and a set of capacitors with a suitable value is connected across the stator's terminals. Stator winding is connected to grid via a bidirectional converter made up of two PWM VSI connections made back-to-back via a DC link.

The fixed speed induction generator design was the first and most widely used idea for producing wind power. This topology, commonly referred to as the "Danish" principle, employs a squirrel-cage rotor configuration in wind turbines. This strategy has been selected due to the cage rotor principle's flexibility, low costs, exceptional reliability, brushless rotor construction, simplicity of maintenance, and no need for excitation by using external DC source [15]. But a comparatively constant slip of about 1% is the most significant drawback in this configuration.

In other words, the turbine's design only permitted a set operating speed. The majority of wind turbines which use a fixed speed induction generator today have blade pitch controls that allow them to modify the blades to restrict the maximum power and speed. Nevertheless, the mechanical components' reaction times frequently hinder the system's ability to react quickly to wind gusts. This feature of the wind turbines, which use a fixed speed induction generator is primarily responsible for the instability of the output power and necessitates a very robust grid in order to maintain continuous operation. The quality of the power which is delivered to grid is the primary issue, in other words, the ratio of active to reactive power provided to the client. The problem is that the induction generator does not generate leading reactive power but rather generates lagging reactive power when it operates normally. Generation of reactive power and correction of power factor are currently accomplished on a minor scale by adding a group of capacitors with different ratings and sizes and adjusting their on/off times to achieve grid demand. However, this temporary solution would not be able to eliminate the reactive power generation issue if conventional power sources were to be entirely replaced by wind turbines with induction generators [5].

The utility giant PacifiCorp came up with a new solution in 2003 that included a new method titled D-VAR that could continuously provide up to ±8 MVARs of power. It's still unclear whether this system, which is solely based on advanced power electronic technology, is able to generate sufficient reactive power for wind turbines that are based on induction generators. When operating, wind turbines, which use fixed speed induction generators, produce a comparatively loud amount of noise. The issue stems from the fact the level of noise generated by the friction of air between the blades and their rotational speed are directly correlated.

The most obvious answer is to enable variable speed operation for the turbine to get rid of few of the issues with wind turbines which use fixed speed induction generators. The squirrel-cage induction generator can be operated at variable speeds in the simplest way possible by adding a bidirectional converter between grid and turbine. figure 2. has shown a squirrel cage induction generator has been connected to grid by using bidirectional converter [16].

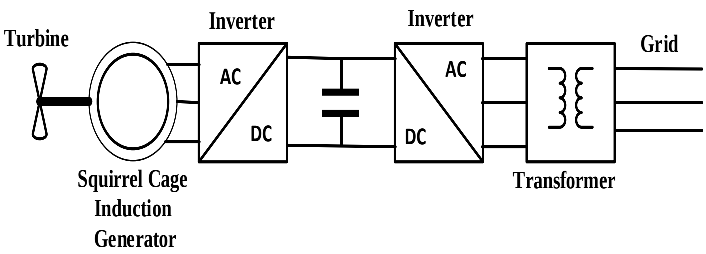

Figure 2. Squirrel cage induction generators with an indirect grid connection.

With this topology, the generator can operate at a speed that is directly proportional to the speed of wind, independent of the frequency of the grid. In this mode, MPPT is used to operate continuously over a wide range of wind speeds for getting maximum power [17].

The benefits of this system are the capacity to fully utilize wind power and the absence of a capacitor bank because the generator can get the reactive power it requires from the dc link capacitor. However, the power converter might be costly due to its size.

The machine side converter's control system provides reactive power in addition to control torque to keep the machine magnetized. The grid side converter control system has two tasks: the first one is to control the voltage of DC link, while the second one is to control the active and reactive power which is delivered to the utility; however, there are some disadvantages for using a squirrel cage induction generator as follows:

1. Complex system control requires a thorough understanding of the generator's parameters, which change with frequency, temperature, and magnetic saturation.

2. The stator side converter must be excessive (35–45% of nominal power) for supplying the machine's magnetizing requirement.

Utilizing the power converter on the rotor side of an induction generator with a wound rotor can result in a smaller power converter. Therefore, a wound type rotor is the most effective way to achieve variable-speed operation. A doubly fed induction machine (DFIM) is the name given to this kind of machine.

3.2. Doubly Fed Induction Generator (DFIG)

A doubly fed induction generator (DFIG), which depends on the wound rotor induction generator, is an alternative to squirrel-cage induction generators and synchronous generators [18]. Doubly fed induction generator (DFIG), in which winding of rotor has been connected to grid through a bidirectional converter while the winding of stator has been connected to grid directly [19]. Although thyristor converters have limited performance, they can still be used. In order to keep the machine magnetized, the rotor side converter has two tasks: the first one is to control the torque, while the second one provides a portion of the reactive power. Conversely, the aim of grid side converter is to regulate the voltage of the DC link. Since rotor slip can use it to regulate speed rotation. In wind turbines which use variable speed, it is very helpful when used as electromechanical converters [20]. Generally, for an induction machine, winding of stator has been connected to an AC source to produce a rotating magnetic flux. The stator's and rotor's total winding count will determine how much of an emf is produced in the rotor as a result. As a result, the rotor emf can be written as:

$$E_{rotor} = E_{stator} \frac{N_{rotor}}{N_{stator}} s \quad (4)$$

The speed of rotation for machine can be written as:

$$\omega_r = \omega_{sync}(1 - s) \quad (5)$$

Consequently, It is able to show that the power in the rotor windings can be used to control the slip:

$$s = \frac{P_{rotorcircuit}}{P_{airgap}} \quad (6)$$

The control of variable-speed for a wound rotor induction generator depends on the equation above. Controlling the amount of slip requires having control over the rotor's energy consumption. This is accomplished by using an outer circuit to the winding of rotor via slip rings. winding of rotor can be connected to either grid via a bidirectional converter or resistive load. By recycling the amount of slip energy, the rotor slip recovery operates as the speed controller in both cases. The speed can be reduced by extracting more slip energy, such as through increased rotor copper loss. When compared to a conventional asynchronous machine, DFIG offers a number of benefits in applications of wind turbines. Firstly, Because of a power electronics converter controls of the current of rotor, DFIG has the ability to import and delivery reactive and active power. This helps the machine to keep the grid operating even in the case of extreme voltage fluctuations and has a significant impact on stabilization of power system. It also offers potential benefits for lowering mechanical configuration stresses and reducing noise. Secondly, the asynchronous machine can maintain high efficiency and grid synchronization even when its speed varies thanks to the control over currents of rotor in addition to control over voltages of rotor. Thirdly, the main benefit of the DFIG is that the power electronic converter only needs to handle a small percentage of the machine power, typically 25–30%. The stator supplies the remaining power directly to the grid [21]. As a result, the converter is less expensive than other variable-speed drives. The most significant benefit of DFIGs is that they allow regulation of frequency, which is necessary if wind turbine is to eventually be the only source of electricity in the future.

Figure 3. has shown the DFIG wind turbine simplified schematic. Current has been drawn from the windings of rotor via the slip rings to enable variable-speed operation. The turbine generates the power that feeds into the rotor windings, which is subsequently fed back via a back-to-back converter. The converter's rating dictates the wind turbine's speed range since it regulates how much power is taken out of the rotor.

DFIG can be controlled with great flexibility. Since they first appeared, many studies have been conducted to optimize the performance of DFIG which are use in wind turbines, that have shown to be a popular alternative to fixed speed asynchronous generator configurations. Above all, the wind turbine's output power depends on the tip speed ratio. Nevertheless, only a specific tip speed ratio value allows for the extraction of the absolute highest possible power.

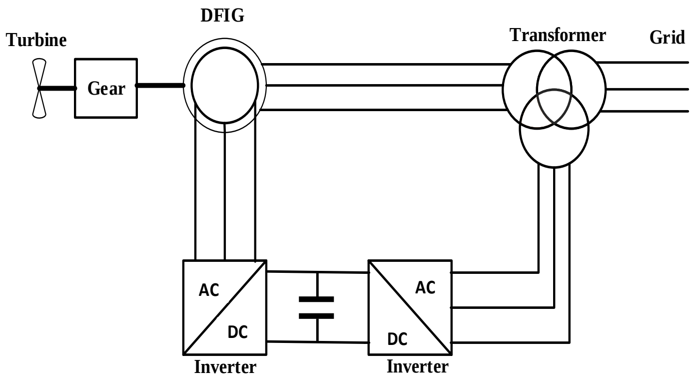

Figure 3. Doubly fed induction generators wind turbines.

The highest possible power for any other speed of wind can only be achieved as soon as the rotor is allowed to rotate in proportion to speed of the wind. As a result, there are two ranges in which the DFIG operates: under and over TSR_{opt}. Both control of rotor speed and control of blade pitch are required for the DFIG to operate at high efficiency.

In general, the stator side output voltage frequency is expressed as follows:

$$\omega_s = \omega_m \mp \omega_r \tag{7}$$

In order to maintain the TSR_{opt} when the wind is low, the rotor rotates in proportion to the wind speed with the blades fixed at a constant pitch. In this instance, TSR is optimized because the frequency of rotor is adjusted to increase or decrease speed, while frequency of grid determines frequency of stator. But as soon as the wind picks up, the rotor frequency is changed in accordance with the maximum power limit, and the blade pitch is continuously altered to limit the maximum power.

Note that at s=0, the power of stator is as high as possible. To maintain optimal value of TSR, rotational speed of rotor must likewise increase as wind speed does. Under these conditions, the DFIG operates at super synchronous speed (s<0). The power flows to the grid through both the stator windings, the rotor windings and their converter. Both windings of rotor and their converter, as well as windings of stator, carry the power to the grid. With reduced speeds of wind, the blades should rotate at a sub-synchronous speed (s>0). Under these conditions, The converter of the rotor will draw power from the grid connection in order to excite the rotor winding.

Mathematical model for DFIG can be written as:

$$V_{ds} = \frac{d\psi_{ds}}{dt} + R_s.I_{ds} - \psi_{qs}\omega_r \tag{8}$$

$$V_{qs} = \frac{d\psi_{qs}}{dt} + R_s.I_{qs} + \psi_{ds}\omega_r \tag{9}$$

$$V_{dr} = \frac{d\psi_{dr}}{dt} + R_r.I_{dr} - \psi_{qr}(\omega_m - \omega_r) \tag{10}$$

$$V_{qr} = \frac{d\psi_{qr}}{dt} + R_r.I_{qr} + \psi_{dr}(\omega_m - \omega_r) \tag{11}$$

R_r: rotor resistance (Ω)

ω_m: mechanical angular speed(rad/sec)

$$\frac{d\omega_m}{dt} = \frac{1}{J}[T_e - T_l - B.\omega_m] \tag{12}$$

B : friction coefficient (N·m·s/rad).

J : inertia of motor(kg·m²).

ω_m : mechanical angular rotor speed (rad/sec).

T_e , T_l : electromagnetic , load torque(N.m) [22].

As a result, The following advantages are provided by this DFIG over synchronous generators:

1. lower cost of inverter because of inverters must control power of slip for rotor; therefore inverters normally supply 25% of the system power overall.

2. Lower inverter filter costs because of inverter harmonics make up a smaller portion of system harmonics overall and filters have a 0.25 p.u. maximum system power rating.

3. This machine's stability and robustness in the face of outside disruption.

3.3. Brushless Doubly Fed Induction Generator (BDFIG)

When it comes to modern wind turbines, the BDFIG offers an intriguing substitute for the widely used conventional DFIG. Although the operating characteristics of these two generator systems are similar, the BDFIG has some advantages over the other. These advantages include increased robustness and reliability as well as a lower maintenance requirement because it does not have brushes or slip rings. The basic concept of the BDFIG is to combine two induction machines with different numbers of poles with one electromagnetic field in the air gap within one frame. Figure 4. has shown the BDFIG wind turbine simplified schematic.

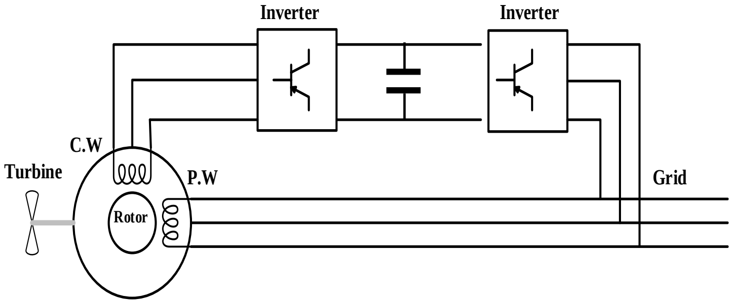

Figure 4. Brushless doubly fed induction generators wind turbines.

The modern BDFIG comprises of two stator windings that are electrically and magnetically uncoupled; to prevent direct coupling, their pole numbers are arranged differently. Modern BDFIG has a unique nested-loop rotor design [23-24]. first winding of stator, called the power winding, is connected to grid directly so it operates at grid frequency, while the second winding of stator, called the control winding, is connected to the grid via back-to-back converter. The frequency converter comprises of two back-to-back voltage source inverters; the inverter has connected to the control winding [25]. The power winding has transferred about 75% of the power from BDFIG to the grid, While the control winding flows through a small portion of power equal to thirty percent of the total power of the BDFIG [26]. The basic aim of the control winding is the ability to control the speed over and under the synchronous speed of the machine. It has the ability to regulate current of the rotor [27]. which is induced through the power winding due to the special design of this machine. The nested-loop, is made of bars of aluminum or copper, which are all made a single side short circuit.

The rotating magnetic flux in the air gap, is produced by two winding of stator that travels in the opposite directions. Consequently, two electromagnetic torques can be produced that act on the shaft of the BDFIG. However, these torques must be variable quantities in order to permit variable speed operation. The generator's total torque can be adjusted to control the required operating speed either by varying the magnitude of voltage that is applied across control winding or by varying frequency. The control and power windings are induced to two excitation voltages during normal operation. Moreover, the frequencies of these voltages are typically different. As a result, the BDFIG mechanical speed is dependent on both the power winding and the control winding frequency. The next equation provides a general expression for the mechanical speed of BDFIG.

$$\omega_m = \frac{120(f_p+f_c)}{p_p+p_c} \tag{13}$$

Where f_p, f_c frequency of power and control winding, respectively, p_p, p_c Number of pairs of poles in the power winding and control winding, respectively.

The rotor interconnection in the BDFTIG determines whether the two frequencies combine additively or subtractively. However, a positive sign for frequency of control winding is preferred in the generation mode. The direction of rotation of the shaft is opposed by the rotational sequence of the stator magnetic field of the control winding. Therefore

$$\omega_r = \omega_m + \omega_c \tag{14}$$

4. OPERATION MODES OF BDFIG

The BDFIG can be operated in several different operating modes, and this depends on the method of feeding the control winding, because of in all modes the power winding has been connected to grid [28]. These modes are:

4.1. Simple Induction Mode

Control winding is opened, even though power winding is supplied. BDFIG can be thought of as an asynchronous machine, in this asynchronous mode [29]. Keep in mind that the BDFIG performance in asynchronous modes is worse than that of conventional asynchronous machines with comparable pole numbers due to a larger flux leakage brought on by a special rotor design.

4.2. Cascade Induction Mode

In cascade operation mode, either power winding or control winding must be shorted at terminals of the BDFIG, and the other is supplied. In more than 95 % of cases, the power winding has been supplied from grid, while control winding has been shorted. Actually, two asynchronous machines can be considered of as the BDFIG in cascade mode. Note that if the power and control winding are supplied at the same time, this case is called double cascade mode.

4.3. Synchronous Operation Mode

It is the operating mode that BDFIG is designed to operate in it, both of control and power winding have been supplied into the BDFIG together. power winding has been connected to grid directly (constant frequency and voltage), while control winding has been connected to grid via a bidirectional converter [30-32]. The control winding in this mode takes the place of the excitation winding in the synchronous machine. In synchronous operation mode it should be noted that in order for synchronous operation to occur, both the magnetic flux has induced current in rotor and has induced current in power, control winding, respectively, must coincide [33]. As a result, they had to have created the same phase-delay and frequency between consequent rotor nests.

The BDFIG can operate in super-synchronous operation mode, wherein rotor receives power from both stator windings. The BDFIG can operate in a sub-synchronous operation mode at positive control winding frequencies, where power is supplied by the power winding and generated by the control winding. or vice versa [34].

5. ADVANTAGES & DISADVANTAGES OF THE BDFIG

Like other electrical machines, the BDFIG is characterized by advantages that favor its use compared to other types. At the same time, there are still some disadvantages that researchers in this field are trying to overcome.

5.1. Advantages of the BDFIG

1) The power of bidirectional converter is low, about 30% of total power of the BDFIG [34], and thus:

- Reduced capital cost of the system due to the lower cost of the bidirectional converter.

- Reduced losses in the bidirectional converter used in the BDFIG compared to the losses resulting from a bidirectional converter whose power is of the order of the total power of the machine.
- Reduced harmonic pollution resulting from the bidirectional converter due to its lower power, as well as reduced cost of the filter used to eliminate harmonics due to the lower power of the filter connected to this bidirectional converter.

2) Getting rid of the brush and slip-ring in the rotor of BDFIG, which is of the squirrel cage type with a special design (nested-loop), thus:

- Reduced need for periodic maintenance operations, which is reflected in lower periodic maintenance costs, which are usually high, especially if the wind turbines are installed at sea(offshore).
- A better investment for the wind turbine, as the operating period of the turbine increases due to reduced maintenance times because there aren't any brushes or slip rings, and thus a higher efficiency [35].

3) The possibility of generating at speed ranges higher or lower than the synchronous speed of the BDFIG, through control of the control winding.

4) The possibility of controlling the power factor of BDFIG and reactive power consumed in the machine by controlling the control winding.

5) When the BDFIG is operated in synchronous mode, it has the characteristics of a synchronous machine, thus:

- Possibility of controlling both reactive and active power.
- The rotation speed of the BDFIG is not affected by the mechanical torque applied to the machine axis.

6) The squirrel-cage BDFIG is characterized by its high robustness and reliability, in addition to its tolerance to higher temperatures compared to the wound-rotor used in DFIG that are sensitive to high temperatures.

7) The possibility of operating the BDFIG as an asynchronous machine, and this is done using the power winding only in the event that the bidirectional converter fails to operate.

5.2. Disadvantages of the BDFIG

1) The BDFIG will be less efficient compared with its DFIG count part, by replacing to a reluctance type rotor from an induction one, efficiency could be raised.

2) The difficulty and complexity of designing the squirrel cage rotor with its own design (nested-loop) and thus its high costs.

3) Increased size of the BDFIG compared to a traditional induction machine of the same power.

6. RESULTS & DISCUSSION

This paper has been presented to review the various technologies for generators employed in wind turbines. Because variable speed machines, which result in increased power capture and less mechanical stress, are in great demand. BDFIG is a major player in the market today because, in contrast to variable speed wind turbines, only 30% of the power produced goes through the converter topology. This results in a reasonable cost savings when compared to the low cost of nearby converters and power switches. SCIG has grid-wide short circuit issues. The PMSG wind turbine generator without the gearbox is the best when it comes to overall efficiency, durability, dependability, and market availability, Since they are larger in size.Table 1. has shown comparison of different type of generators.

Table 1. Comparison of different type of generators

Type of Generators	Strengths	Weakness	Capital Cost	Maintenance Cost	Application Range
Synchronous generator	There is no gearbox. Active and Reactive power can be controlled.	Needs DC current for excitation. An AC/DC/AC power converter is required.	High	High	Standalone wind turbines
Permanent magnet synchronous generator (PMSG)	There are no brushes and gearbox. Active and reactive power can be controlled.	Can not connect directly to grid. Generator is big size and heavy. Permanent magnets are required.	High	Low	Medium wind turbines
Squirrel cage induction generators (SCIG)	No need for excitation. Can connect directly to the grid. Low cost.	Gearbox is unavoidable.	Very Low	Very low	Small wind turbines
Doubly fed induction generators (DFIG)	No need for excitation. Speed range is limited from -30% to 30% around synchronous speed. Active and reactive power can be controlled. The power of bidirectional converter is low, about 30% of total power of the DFIG.	Slip rings are unavoidable. A gearbox is required.	Medium	High	Large wind turbines
Brushless doubly fed induction generators (BDFIG)	The power of bidirectional converter is low, about 30% of total power of the BDFIG. Gearboxes, brushes and slip rings are not required. The possibility of generating at speed ranges higher or lower than the synchronous speed of the BDFIG. Active and reactive power can be controlled.	The difficulty and complexity of designing the squirrel cage rotor with its own design (nested-loop) and thus its high costs. Increased size of the BDFIG compared to a traditional induction machine of the same power.	Medium	Low	Large wind turbines

As table 1. illustrates, synchronous generators have the highest capital costs, because a full-scale AC/DC/AC power converter and an excitation system are required. While squirrel cage induction generators (SCIG) have the lowest capital costs because of its simple structure, in addition to absence of power electronic converters. Regarding to maintenance cost, synchronous generators have the highest maintenance cost, As the brushless doubly fed induction generators (BDFIG) have the lowest maintenance due to absence brushes and slip rings. Regarding to nominal power rating brushless doubly fed induction generators (BDFIG) & permanent magnet synchronous generator (PMSG) have the highest power rating which can reach to 15 MW, while squirrel cage induction generators (SCIG) have the lowest power rating about 1 MW.

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