Various Wind Turbine Generator Systems and their Suitability for Smart Grid Integration

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Abstract—Over the past three decades global energy consumption has increased drastically due to industrialization and automation. On the other hand conventional energy sources like fossil fuel are ever depleting. Therefore, industry and scientist are focusing on renewable energy sources – those address twin challenge of energy security at the same time minimizing pollution caused by excessive fossil fuel usage. Over past three decades renewable energy installations like wind and solar energy are becoming popular globally. This exponential rise in renewable energy installation posed challenges to grid stability, reliability and its power quality. This is due to distributed and intermittent nature of renewable energy generation. There is continuous evolution on wind turbine technology and associated power electronics to address these challenges economically. Present days wind farms consist of various types of turbine technologies featuring fixed speed, variable speed, semi variable speed operations. The study of various wind turbine generators is necessary in order to understand its suitability in smart grid integration.

Keywords—Direct Drive Technology; Distributed Generation; Doubly Fed Induction Generator; Fixed speed Operation; Hybrid Direct Drive Technology; Power Quality; Renewable Energy; Smart grid.

I. INTRODUCTION

Over the past three decades, global energy generation and consumption have accelerated to unprecedented degrees. In India a large amount of electricity is used for residential, commercial and industrial process applications every day. The use of renewable energy (RE) sources in power generation have increased significantly due to lack of conventional energy sources, environmental issues and rise in the cost of fossil fuels. Out of all renewable energy sources solar, small hydro power and wind are having potential to provide solution to increasing power demand [1].

Most of the renewable energy sources are intermittent in nature, have less capacity, and are installed in a more distributed manner at different locations. Literature shows that out of different renewable energy sources, wind energy is one of the fastest growing technologies in the world, as the generation of wind power is clean, non-polluting and it does not produce any by-products harmful to the environment. Today, the conventional and modern wind turbine generators, working on different technologies are available and being used for power generation. Each technology is having certain features, therefore it is necessary to study, understand and disseminate the knowledge of different wind turbines technologies before integrating into the smart grid [1][14][19].

Nevertheless, most of the existing grid networks consisting of transmission and distribution networks are not capable to handle excess penetration of RE energy due to distributed and intermittent nature of renewable energy generation. To address this, efforts are being taken to make wind turbine generate grid friendly power that comply HVRT, LVRT and other grid codes. Further due to bidirectional nature of energy flow conventional grid infrastructure needs to be upgraded to smart grid infrastructure. The smart grid infrastructure helps to handle bidirectional flow of energy from and to the consumer [17][18][19]. Further, with the help of modern IOT infrastructure smart grid helps in better demand supply management that encourages energy efficiency, better power quality, improved reliability [15][16].

The rest of the paper is organized as follows: section 2 explains the different types of wind turbine generator technologies used for power generation along with their features. The comparisons of different types of wind turbine generators technologies, their comparison and suitability study for smart grid integration are discussed in section 3, followed by the conclusion.

II. WIND TURBINE GENERATOR TECHNOLOGY

The wind turbines are classified into three different classes based on speed of operation – such as fixed speed, variable speed etc.: axis of operation – such as horizontal, vertical axis and installation location of wind turbines like on shore or offshore. The technological evolution of wind turbine generators is mainly based on its speed of operation. The classification of wind turbines based on speed of operation is as shown in Fig. 1 [1].
variable speed wind turbines are more expensive, this type of turbines operates at maximum aerodynamic efficiency than constant speed turbines [5]. A typical curve of power coefficient “Cp” against tip speed ratio “λ”, for a fixed speed and modern variable speed wind turbine is shown in Fig. 3, A and B respectively [2][6]:

- The Tip Speed Ratio: ‘λ’ is defined as the ratio of speed of the tips of wind turbine blades to wind speed [2]. It is given in (1).

\[
λ = \frac{V}{\omega R} = \omega R / V
\]  

(1)

Where ‘ω’ is angular velocity of blades in radian /sec., ‘R’ is rotor radius in meter and ‘V’ is wind speed in m/sec.

In order to maximize the power generation it is necessary to maintain constant optimal tip speed ratio (λ) i.e. if wind speed increases rotor speed should also increase thereby maintaining a constant value of tip speed ratio [2].

Fig. 3. Power coefficient (Cp) Vs tip speed ratio (λ) curve for fixed and variable speed three blade wind turbines [2] [6]
The coefficient of performance, $C_p$, is defined as the fraction of energy extracted by the wind turbine out of the total wind energy that would have flowed through the area swept by the rotor if the turbine had not been there and it is calculated using (2) [2].

$$C_p = \frac{P_t}{P}$$  \hspace{1cm} (2)

The coefficient of performance $C_p$ has a theoretical maximum of 0.59. It means maximum only 59 percent of wind power can be converted to useful energy by a wind turbine. This maximum theoretical $C_p$ was first formulated in 1919 by Betz and it is applicable to all types of wind turbines [2].

For a fixed speed wind turbine, where $\omega$ is constant, which corresponds to a particular wind speed. For all other wind speeds the efficiency of the turbine is reduced [3]. The aim of variable speed wind turbines is to always run at optimal efficiency, keeping constant value of tip speed ratio ‘$\lambda$’ that corresponds to the maximum $C_p$, by adapting the blades velocity to the wind speed changes. Hence, variable speed wind turbines are designed to operate at optimum energy efficiency, regardless of the wind speed [2]. The conversion efficiency of variable speed wind turbine generator is maximum due to variable speed operation. Therefore, variable speed wind turbines are preferred over constant speed wind turbines. The key advantages of variable speed generators (VSGs) compared to fixed speed generators (FSGs) are [1]:

- Cost effective and provide simple pitch control: The controlling speed of the generator (frequency) allows the pitch control time constants to become longer, reducing pitch control complexity and peak power requirements. For lower wind speed, pitch angle is usually fixed where as pitch angle control is used to limit maximum output power at high wind speed.
- Improved power quality and Reduced Mechanical stresses: In case of VSGs, gusts of wind can be absorbed, creating an elasticity that reduces torque pulsations. It reduces electrical power variation i.e. flicker, which results in improved power quality.
- Reduction in acoustic noise: In VSGs acoustic noise gets reduced because of low speed operation possible at low power conditions.
- Improved overall system efficiency: The output power curve of a turbine depends upon turbine speed and wind speed as shown in Fig. 4.
- In variable speed wind turbine generators, turbine speed changes on the basis of wind speed to maximize output power. Operation at the maximum power point can be realized over a wide power range. As a result, energy efficiency improvement up to 10 percent is possible as shown in Fig. 5 [2].

Fig. 5: Improvement in efficiency due to variable speed operation [2]

C. Semi variable speed wind turbine generator- Doubly Feed Induction Generator (DFIG)

Fig. 6 shows, the various parts of DFIG generator. It consists of a variable speed wind turbine with a Wound Rotor Induction Generator (WIRG) and a partial scale power converter on the rotor circuit [8]. DFIG consists of a four quadrant ac to ac converter based on insulated gate bipolar transistors (IGBTs) connected to the rotor windings. It consists of a stator connected directly to grid and a rotor via slip rings is connected to grid through four quadrant ac to ac converter based on IGBTs. The DFIG technology with a partial scale power converter is a simple and highly controllable way to transform mechanical energy from the variable speed rotor to a constant frequency electrical utility grid. The power converter controls the rotor frequency and thus the rotor speed. Typically, the variable speed range is +30 percent around the synchronous speed. The DFIG technology is more popular and connected to the national grid networks due to its ability to supply power at constant voltage and frequency during varying rotor speed (wind speed).

Fig. 6: Doubly Feed Induction Generator [4]

The DFIG technology is very popular amongst present day main stream wind turbines manufacturers. DFIG is becoming popular due to its ability to drive down the cost while helping in addressing the modern day grid code requirements. The largest rated capacity for the commercially available wind turbines based on DFIG has capacity up to 5 MW and development of higher capacity up to 7 MW is in process mainly for offshore applications [8]. The DFIG wind turbine generator system offers the following advantages:

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Economic: The power electronics circuits used in DFIG are simple. The rating of the power electronic converter typically 25 to 30 percent of the generator capacity, which makes DFIG concept attractive and economical [8].

- Improved system efficiency
- It is possible to control power factor at lower cost because the DFIG system basically operates similar to a synchronous generator with four quadrant converter and induction machine.
- DFIG has a complete control of active and reactive power. A partial scale four quadrant electronic converter in the rotor circuit enables in control of active and reactive power of the generator.

The majorities of wind turbines currently installed are based on DFIG and consists of some type of gear box. The gear box is used to increase the rotation speed of the generator to match the frequency of the grid. In DFIG, the generator speed increases with the gear ratio so that the reduction in machine weight is adjusted with gearbox weight [10]. For example, the wind turbine operates at a speed of 15 rpm and the generator is designed to operate 1200 rpm (for 60 Hz frequency) [11]. An up speed gearbox of 1:80 is required to match the speed/torque of the turbine with DFIG [10]. The disadvantages of DFIG technology are [8]:
- A gear box is necessary in DFIG. A gearbox is prone to failure due to various reasons like heat dissipation due friction, misalignment of moving parts and lack of lubrication. It also requires regular maintenance and generates audible noise [10]
- The slip ring is used to transfer the rotor power by means of a partial scale converter. Which requires a regular maintenance, and may result in machine failures and electrical losses
- Over current protection is required during grid fault conditions as a large amount of stator and rotor current may destroy the assembly

D. Fully Variable speed wind turbine generator

Direct drive is a variable speed wind turbine whose generator connected to the grid through a full scale power converter. The generator type can be either self or electrically excited (EE) machine or the permanent magnet (PM) machine. The world market share of the direct drive generator system has been around 20 percent, which is a sum of the share of direct drive EE machines as 15 percent and direct drive PM machines as 5 percent, in 2004 [7]. In the direct drive wind technology, generator rotates at a low speed, and the generator shaft is directly connected on the turbine rotor hub to form a gearless unit [12]. As there are fewer rotating parts, the mechanical stress is reduced and the equipment’s service life, reliability and efficiency are increased [12]. A special type of generator is required for direct drive systems which operates at low speed and high torque operation require multi poles. For the implementation of large number of poles, a larger rotor diameter is required and for a higher torque, a larger machines volume is required, so that the torque density could not be further significantly increased [8]. The direct drive wind turbine generators are designed with a large diameter and a small pole pitch to increase the efficiency, to reduce the weight of the active parts and to keep the winding losses small [7].

The major advantages of direct drive wind turbine generators are simplified drive train system, the high overall efficiency and high reliability due to omission of gearbox [8] [12]. The direct drive PM generator system is most suitable for wind turbine application due to low maintenance cost, light construction and maximum energy yield. The arrangement of DD is shown in Fig. 7 [7].

In direct drive wind turbine generators, the relation between power output “P”, torque “T” and rotor angular velocity “ω_m” is given by (3),

\[
P = T \cdot \omega_m
\]

In the direct drive WTG, rotor is operated at low speed. When scaling up the wind turbine, the rotational speed is decreased more and more considering the tip speed limitation. Due to which in order to scale up the power of the direct drive generator, the torque “T” must be increased in inverse proportion to the decrease of the mechanical angular speed, “ω_m”.

The generator power, “P” can be also defined as a function of the tangential force density “F_d”, the air gap diameter “D_g”, the axial length “l_r” and the mechanical angular speed “ω_m” as given in equation (4):

\[
P = \frac{1}{2} \pi D_g l_r \omega_m
\]
power electronics, since all the generated power has to pass through the power converter. In direct drive the size of electrical generators increases which effectively nullifies some of the weight savings from removing gearbox. The direct drive wind turbine generator is more than 10 times larger than its equivalent capacity geared machine [9]. Moreover, it typically requires the full rated power converters for grid connection. Also the direct drive machine operates at low speed and having some of the drawbacks like high torque rating, large diameter, heavy mass, and high cost compared to the geared generator concept [8]. Nevertheless, DD wind turbine has best ability to deal with issues like power quality, smooth grid integration and adherence to grid code.

E. Hybrid Direct Drive Generator or Multi-bred WTG

In the second half of the 1990s, the first prominent example of a low speed geared drive system: Hybrid direct drive (HDD) or multi-bred was developed and patented by German engineering consultancy Aerody Energy system. The first 5MW multi-bred M5000 consists of a single stage planetary gearbox, a low speed (150 rpm) PMG and single rotor bearing. The prototype was installed in 2004 by Areva Wind [13].

Traditional wind turbine generators with gear box suffer from losses due gear box and the gearless direct drives are heavy and expensive. Neither is suitable in stormy, salt laden winds as far as 300km from shore. The solution is the hybrid direct drive wind generators. HDD is a combination of geared system (DFIG) and direct drive train system (DTS) [12]. The block diagram of hybrid direct drive wind energy generator is shown in Fig. 8.

Some of the HDD wind turbine generator consists of a simple gearbox and a generator of a size nearly same as the ones used for in DFIG. The other type of hybrid direct drive wind turbine generator consists of multiple generators. This type of DTS results in a more compact of the arrangement between the gearbox and the generator as compared to any other DTS [12]. In hybrid direct drive option, the generator size and speed lie in between DD and DFIG. By grafting together the best aspects of DFIG and DD technologies, hybrid medium speed drive trains promise to be smaller, lighter, more reliable and more efficient than their pure play counterparts in the 3-10MW class. It requires full rated power electronics convertor. These hybrids are cheaper, but they would ratchet up output while cutting installation and maintenance costs and so shrink the overall cost of energy (CoE) [13].

This technology helps to reduce the generator size by offering increased rotor speed and has similar ability to handle grid codes like DD technology.

III. SUITABILITY STUDY OF WIND TURBINE GENERATOR TECHNOLOGIES IN SMART GRID

The comparison of all four types of wind turbine generator technologies on the basis of its physical and performance parameters is given in table 1. The installation of renewable energy generators, especially wind is more popular. The numbers of wind farm installations are increasing in order to achieve balance between power generation and demand. So the integration of different wind turbine generator technologies into existing power grid is the challenging task. Fixed speed wind turbine generators are robust, traditionally used and having ability to provide power at constant frequency during constant wind speed. A sudden variation in wind speed results in power fluctuations which results in power quality problems which makes them less grid friendly. The cost of fixed speed generators is less as compared to other turbine generators of the same capacity working on semi variable or variable speed technology. Simple power electronics circuits are used and having poor control over active and reactive power. The control over reactive power is achieved using external capacitor bank. They are generally less suitable for onshore installation and therefore not popular in this category. The conversion efficiency of fixed speed generators is poor whereas that of variable speed wind turbines like Doubly Feed Induction Generators (DFIG), Direct Drive (DD) and Hybrid Direct Drive (HDD) turbine generators is much better – making them technically as well as commercially attractive. The gear box is used in Doubly Feed Induction Generator (DFIG) which leads presence of various gear box related issues during the prolonged operation. So it requires regular maintenance though the installation is economical. The partial scale power electronic convertor is used and has control over active and reactive power hence on power factor in the presence of LVRT capability. This makes DFIG more grids friendly and it is suitable only for onshore installations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>FSIG</th>
<th>DFIG</th>
<th>DD</th>
<th>HDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronic converter</td>
<td>Simple</td>
<td>Partial scale</td>
<td>Full scale</td>
<td>Full scale</td>
</tr>
<tr>
<td>Reliability</td>
<td>Fair</td>
<td>Good</td>
<td>Better</td>
<td>Better</td>
</tr>
<tr>
<td>Power Efficiency</td>
<td>poor</td>
<td>Good</td>
<td>Better</td>
<td>Better</td>
</tr>
<tr>
<td>Robustness</td>
<td>Good</td>
<td>Good</td>
<td>fair</td>
<td>fair</td>
</tr>
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<td>----------------------------</td>
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</tr>
<tr>
<td>Grid Friendly: Active and</td>
<td>Fair</td>
<td>With</td>
<td>With</td>
<td>With</td>
</tr>
<tr>
<td>Reactive Power Control</td>
<td>LVRT</td>
<td>LVRT</td>
<td>LVRT</td>
<td></td>
</tr>
<tr>
<td>Economy: CAPEX</td>
<td>Low cost</td>
<td>Moderate</td>
<td>Costly</td>
<td>Costly</td>
</tr>
<tr>
<td>Generator Rotor Size</td>
<td>Small</td>
<td>Smaller</td>
<td>Big (near</td>
<td>Big (smaller</td>
</tr>
<tr>
<td></td>
<td>than DD)</td>
<td>than DD)</td>
<td>10 times of DFIG)</td>
<td>10 times of DFIG)</td>
</tr>
<tr>
<td>Generator Weight Size</td>
<td>Less</td>
<td>Moderate</td>
<td>Heavy</td>
<td>Moderate</td>
</tr>
<tr>
<td>Gear Box</td>
<td>Present</td>
<td>Present</td>
<td>Not Present</td>
<td>Planetary Gear box</td>
</tr>
<tr>
<td>Maintenance cost: OPEX</td>
<td>Less</td>
<td>More than DD</td>
<td>Less than DFIG</td>
<td>Less than DGIG</td>
</tr>
<tr>
<td>Preferred Installation</td>
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<td>On shore</td>
<td>On/Off shore</td>
<td>Off shore</td>
</tr>
</tbody>
</table>

The Direct Drive (DD) technology is suitable for onshore and for some models offshore installations. The maintenance cost is less as gearbox is not used and replaced by special generator assembly. The size especially rotor diameter is almost ten times more as compared to the wind turbines of same capacity but working on different technology. A full rated power electronics converter circuit is used which helps in making smooth connection or integration to the grid. Hybrid direct drive is also called as multi-bred is a combination of geared and gearless system. It has the combination of simple gear box and multiple generators which makes it very expensive. It suitable for offshore installations as it requires less maintenance. It can form smooth connection or integration with the grid in presence of LVRT. The conversion efficiency of hybrid direct drive wind turbine generator is more than the other wind power generators.

IV. CONCLUSION

Smart grid pilot and deployment is on rise due to its ability to accommodate the excess penetration of renewable along with conventional generators. In this paper, we have discussed traditional used fixed speed and various modern variable speed wind turbine generator technologies. Although, traditional fixed speed induction generator are cost competitive and offer robust operation its popularity is on decline. This is mainly due to its limited aerodynamic efficiency and ability to cope with modern days strict grid codes requirements. Next, even though a power electronic grid compliance solution can be developed for traditional FSIG machines those are less suitable for integration in to the futuristic smart grid which boast concept of better reliability, economics and power quality. Variable speed wind turbine technologies such as DFIG, DD and HDD not only offer higher aerodynamic efficiency but also offer best ability to control active and reactive power by employing active power electronics using IGBT technology. Therefore variable speed wind turbines are best suitable for wind energy integration to smart grid.

REFERENCES