Technical Aspects of Different Grid Connected Wind Energy Conversion System Configurations in Wind Farm

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Abstract: Among all the renewable energy conversion systems wind energy conversion systems becoming most promising area especially at offshore locations due to availability of huge amount of wind power round the clock. This paper summarizes a review and recent advances happening in some most commonly used generators and power converters configurations at offshore/onshore wind farm.A comparison among all the different configurations has been done on the basis of fixed/variable speed operation, MPPT ability, FRT ability, power converter utilization, reactive power compensation, with and without gear-box and current market status.

Keyword: energy conversion systems, wind energy conversion systems, offshore locations, offshore/onshore wind farm, MPPT ability, FRT ability, power converter utilization, reactive power compensation

I. INTRODUCTION

In last few decade years, the renewable energy sources emerged as a best replacement of fossil fuels/nonrenewable sources due to several issues such as limited availability and globally abrupt high price risk, threat of environmental pollution, global warming etc. So the electricity produced byall the renewable energy sources like wind, hydro, tidal, geo-thermal, solar and biomass sources have drawn more attention. Now a day, a lot of research works in progress on renewable energy for power extraction and production. Out of all renewable sources, the wind energy have been become most promising area among the renewable energy sources due to easy availability of the wind in bulk for throughout the year. There are several other reasons like availability in bulk amount, competitive cost, clean and eco-friendly power generations etc. From above mentioned facts,wind comes out as most promising source among all renewable sources.Now a day a lot of research is going on in this area due to their well-established advantages which make it favorite among manufacturers which can be seen from its exponential industrial growth. This results into a win-win situation for both wind turbine manufacturing industries as well as the bulk power consumers market because of cheap and clean wind power generation [11,14,44,46].

The statistics shows that the global cumulative installed capacity has explosively increased from 23.8 GW to 539.6 GW (GWEC Report, 2017).As per the current growth rate trend, it is expected that the cumulative wind capacity could touch about 760 GW by 2020.In recent years, there was a sudden rise in electrical power demand among those countries that are looking for alternate pollution free electrical power.

As a result of that the offshore wind energy system has been evolved as a most promising area among all the renewable sources due to abundant availability of huge amount of wind energy in the sea than at onshore. The histogram graph given in figure 1.2 clearly indicates the bright future of off-shore wind power across the world. The histogram shows that the capacity has increased abruptly from 4.1 GW to 18.8 GW (Wind Report, Global Wind Energy Council, 2017).Offshore wind energy conversion system may use high rating of turbines to capture bulk amount of wind power and can be installed into sea far away distance from onshore [54].

The design, size, locations and type of offshore wind turbines play very important role for maximum wind power extraction. To select most suitable offshore WECS topology the different topologies with respect to their electrical losses, mechanical losses, repair cost and installation cost can be analyzed [51-52,55].

II. GRID CONNECTED WIND ENERGY CONVERSION SYSTEM

Wind Energy Conversion System mainly comprises mechanical and electrical components with their respective control systems so that the system works properly under dynamic conditions.The mechanical wind turbine system used to capture wind power efficiently with the help of properly designed aerodynamically shaped rotor blades which is coupled with electrical generator via a common mechanical shaft.

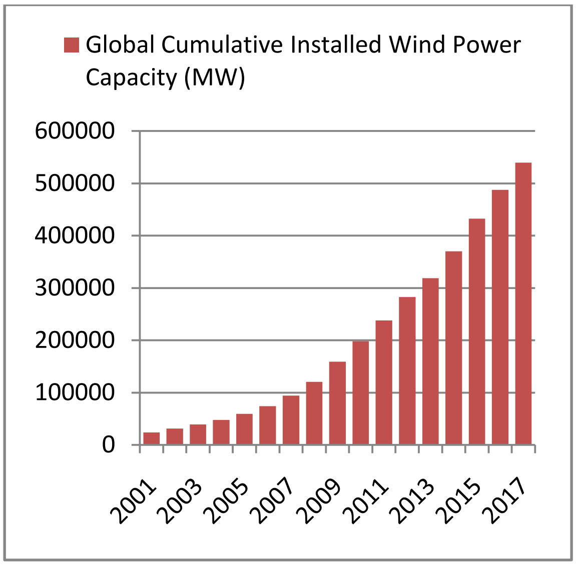

Figure 1.1: Market Trends of Installed Wind Capacity in Mega Watts [54]

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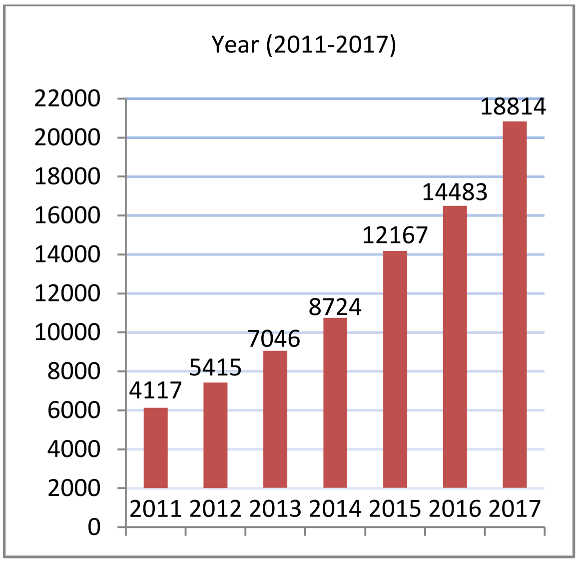

Figure 1.2: Market Trends of offshore Installed Wind Capacity in Mega Watts [54]

The common mechanical shaft is used to transmit mechanical power from wind turbine to generator which further converts this mechanical power to electrical power [27,18,47]. Now by using suitable power transformers and filters this electrical energy transferred to grid at desirable grid voltage and frequency as shown figure 2.1.

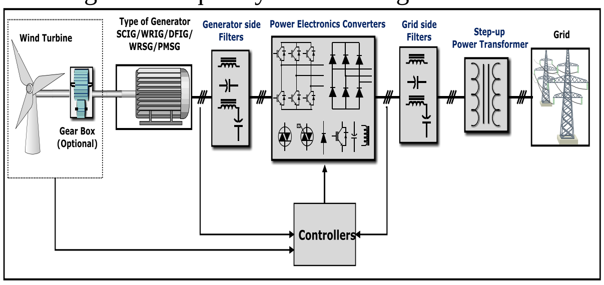

Figure 2.1: A Generalized grid connected WECS

Mechanical System:

The mechanical system composed of many components like tower used to support and hold the whole wind turbine assembly, nacelle, Turbine blades, drive train assembly with gearbox, Mechanical pitch and yaw control assembly etc. The rotor blades converts the wind kinetics energy into mechanical energy by considering many factors like shapes and angle of blades, wind density, wind velocity etc.With the help of Pitch and yaw control, wind turbine may generate maximum mechanical energy efficiency at the given range of rated wind speed. Two mechanical systems with different torque-speed characteristic can be coupled with the help of multistage gearboxes. But gearbox mostly has some serious problems like extensive wear and tear, high noise pollution, regularly much more maintenance with lesser life span and efficiency. The elimination of gearbox is always better option by matching the speed of generator with wind turbine speed often referred as direct drive operation. The direct drive operations have much more efficient than conventional gearbox drive [24,53].

Electrical System:

Here, the electrical system converts the mechanical power into electrical power and transfer it to electrical grid system. The Electrical system of WECS composed of many components which are used for interfacing with the grid connected wind turbines like Generators, transformers, harmonics filters, DC link elements, power converters, cables, consumers load etc. In past three and a half decades, there are many types of generators have been designed like SCIG,WRIG, DFIG, PMSG, WRSG in wind conversion system for electrical power generations with their own advantages in different wind conditions[6].Earlier the fixed high speed operation based WECS mostly used Induction Generators for generation[8].

But now days, synchronous Generators used in low speed due to feasibility of large number of poles. The stator windings of synchronous generators can be designed for any no of poles and size at variable wide range of speed (low, medium, high) which not possible in Induction generators. The power electronics converters interfacing between generator and grid through DC-link capacitors, transformers and harmonics filters may provide many types WECS configurations depending upon grid synchronization parameters. In many configurations, transformers can be optional because sometimes the grid side inverters are able to operate at grid voltage [1,56].

Control System:

Every system either Mechanical or electrical always require some control systems in order to achieve the desirable dynamic and steady state performances. Here, the dynamic and steady state performances of WECS are monitored by controllers which are usually implemented for the switching of generator-side and grid-side inverters. These controllers monitor several mechanical parameters (like rotor speed, rotor blade angle and yaw angle) and electrical parameters (like generator voltage and current, DC-link voltage, grid frequency, current and voltage) [6,20].

A. Fixed and variable speed based WECS Configurations

In today's Modern world, there are many wind turbines topologies available commercially for fixed speed as well as for variable speed WECS configurationswith different kind of generators are as follows:

Fixed speed based WECS Configuration

This configuration is called fixed speed WECS because generator speed varies around only 1% at variable wind speed as shown in figure 2.2. This Danish concept based configuration was the oldest, simple, cheap, robust and reliable. In this configuration, the wind turbine was directly connected to grid without any interfacing of power electronics converters [8]. Here, the power captured by rotor blades of wind turbine was transferred to SCIG which is mechanically coupled to generator with gear box in order to match and cope up the speed difference at variable wind speed. The SCIG further delivered this power to grid at 50Hz /60Hz through the soft-starters and step-up transformer.These fixed speed WECS replaced by variable speed due to some main drawback of this configuration like lower conversion efficiency, requirement of STATCOM for grid code compliance, requirement of multistage gear box to match and cope up the speed difference between turbine and generator, poor LVRT/FRT behavior, more stress on mechanical components under fault condition, wind speed variations reflection in grid [22,50,32].

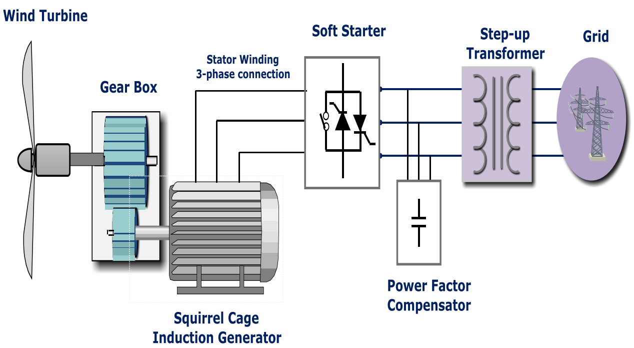

Figure 2.2: Fixed speed SCIG based grid connected WECS

The fixed speed turbine WECS configurations are still in operation and available in MW range to generate the electricity.

Variable speed based WECS Configurations

The variable-speed based operation increases the overall conversion efficiency and minimize mechanical stress on wind turbine components. As a result of which increased the life span and cycle of equipment due less wear and tear with minimum requirement of maintenance caused by wind gusts. [39,28,25].

Semi-Variable based WECS Configuration

There are two kinds of semi-variable WRIG and DFIG based WECS configurations which are employed with partially rated power converters as shown in figures 2.3 and 2.4. The variable speed operation is achieved in WRIG by adjusting the rotor resistance through switching of power converters (Diode-rectifier and Chopper) and limited to 10% of its rated speed. The switching of power converters changes the resistance of rotor winding which affects the torque-speed characteristics of the machine i.e. optislip control method [5,34,33,41].

In DFIG based WECS power is transferred from wind turbine to grid through both stator as well rotor winding of generator as shown in figure2.3. Here, the switching of power converters is employed in the rotor winding in order to change rotor resistance (slip power) which is used for bidirectional power flow (around 30% of its rated power).The main feature of this configuration is that the implementation of MPPT algorithm upto 30% of its rated speed which enhance its conversion efficiency and dynamic performance [42,29].

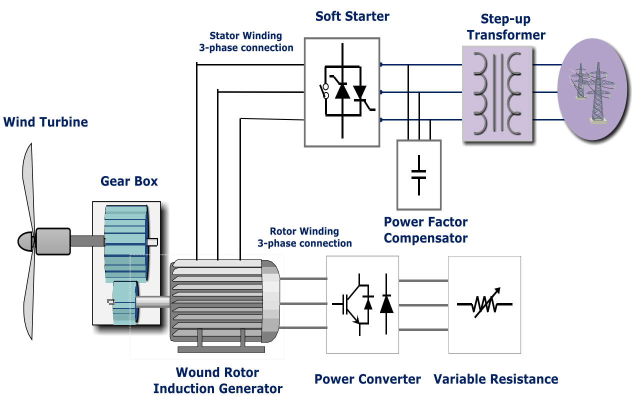

Figure 2.3: Semi- variable speed WRIG based grid connected WECS

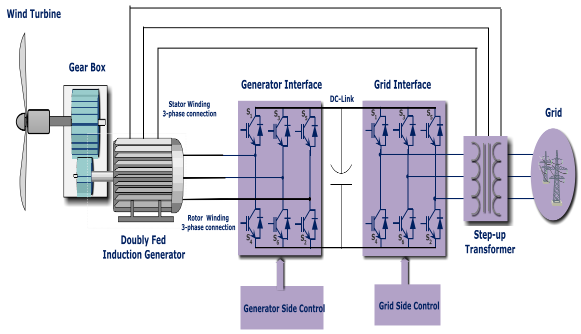

Figure 2.4: Semi- variable speed DFIG based grid WECS

The main drawback of these semi variable configurations is low conversion efficiency, limited speed range, high turbine cost, Rotor circuit power loss, require complex control strategies, Requirement of regular maintenance for gear box and slip ring, frictional loss and high noise, requirement of reactive power compensation and poor ride through capability due to partial utilization (below 30%) of power converters[5,34,49]. But despite of it still there are many manufacturers available in the market like Suzlon Energy, Bard, Acconica,Vestas, Gamesa, Repower, Nordex.Commercially, Repower and Bard company manufacturing the DFIG based wind turbine up to 6MW and 5MW respectively [25].

Full-variable based WECS Configuration

There are three kinds of full-variable SCIG, WRSG and PMSG based WECS configurations which are employed with power converters up to their full capacity as shown in figures. These WECS configurations are fully decoupled and capable to deliver the power to the grid at full range of its rated speed (0% to 100%). Moreover, there is no need of soft starters and power converters able to deliver the required reactive power compensation for grid FRT compliance[23,25,5].The synchronous generators have two types of rotor either electrically excited field windings (WRSG) or permanent magnet (PMSG). In variable speed WRSG based WECS configuration, a 3-phase stator winding is connected to grid through a power converters with indirect two stage conversion (AC-DC-AC) and rotor winding resistance is controlled by choppers (DC-DC) as shown in figure 2.5 and figure 2.6. This WRSG based configuration can be possible either by using a gear box or without a gear box (as a direct drive).

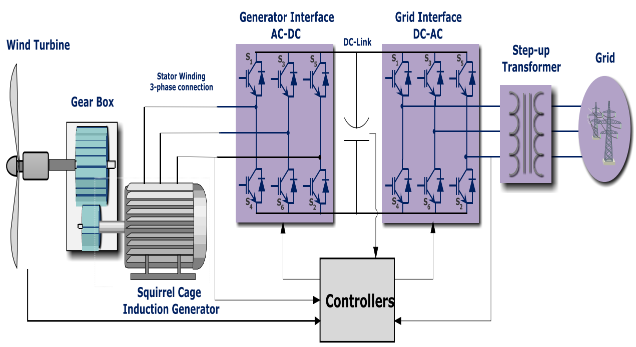

Figure 2.5: Full variable speed SCIG based grid connected WECS

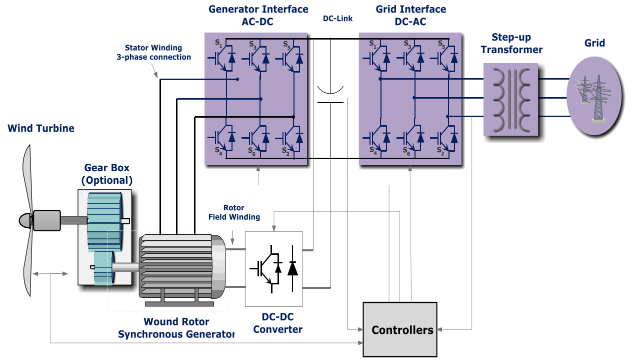

Figure 2.6: Full variable speed WRSG based grid connected WECS

The purpose of multistage gear box to match the speed difference between both generator and turbine speed [9].

At higher rotor speed, WRSG is quite good option with multistage gearbox but when system demands low speed operation then WRSG becomes a costly affair because it require machine with large no. of poles. In order to accommodate large number of poles machine with a big DC excitation system increase its size, volume and weight. So a big size of tower and foundation required to withstand these machines which in turn increase the overall cost of the WECS. Under this situation, system demands a more efficient, reasonable small size and with higher power rating/density electrical machine for direct driven WECS. Therefore, a PMSG based directly driven WECS are more preferable as it has small size more efficient machine than WRSG.

B Direct-Drive PMSG based WECS Configuration

The main difference between multistage gear-drive and direct-drive wind turbines is rotor speed of generator. The direct-drive based WECS deliver power at a low speed and the shaft of generator rotor is directly coupled to the turbine rotor as shown in figure 2.7.After studying several research articles about generators, it is find out that the synchronous generator based WECS have good mechanical capability for direct-drive wind turbines and there is no need of gearbox [17].

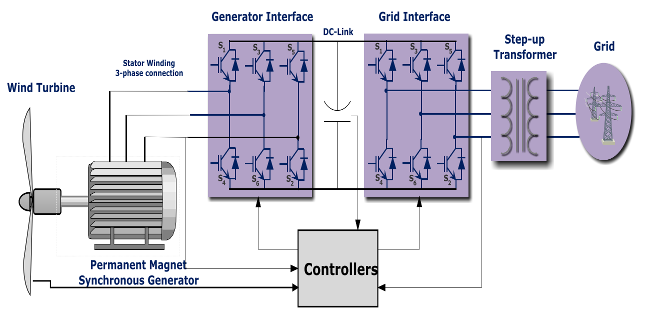

Figure 2.7: Direct driven full variable speed PMSG based grid WECS

Here, the rotor of synchronous machine is directly coupled(mechanically) with wind turbine througha common shaft at a low speed. This feature of synchronous generator will increase the life span of the system with minimum requirement of maintenance. In order to extract more power from synchronous generator at lower speed it is necessary to make a machine of large size with multiple poles so that machine can be able to produce and give higher torque at low speed [57,10,43]. The PMSG have edge over WRSG as there is no requirement of DC Excitation for rotor field winding and with simplified design [35,2]. Therefore, the main advantages of direct-drive PMSG based WECS is the wind turbines have simplified drive train, no gear box, no need of DC excitation, elimination of slip rings and brushes, MPPT ability, high conversion efficiency, highly reliable with low maintenance and full-rating utilization of power converter with reactive power compensation. The main drawback of permanent magnet synchronous generatorsis constant magneticfield due to permanent magnet. As a result of which the generator output voltage can be change with the variation in rotor speed as field control is not possible due to constant field flux [21,30,3,40,31].

III. POWER CONVERTERS TOPOLOGIES IN WIND FARM

On the basis of power conversion strategies, the power converter topologies are mainly classified as Direct and Indirect.Therefore, power conversions which have performed by using of different arrangements of power converters[13].

i) Direct conversion with single-stage AC/AC conversion which includes cyclo-converters and Matrix Converters etc.
ii) Indirect conversion with two-stage (AC/DC and DC/AC) conversion which includes Voltage Source/Current Source half and full controlled converters with or without DC link, passive controlled converters etc.
iii) Another Indirect conversion uses three-stage (AC/DC and DC/DC and DC/AC) conversion which includes Voltage Source/Current Source half and full controlled converters with or without DC link, buck and boost controlled converters etc.

There are some important requirements while choosing power converters topologies in WECS like initial cost which is generally 5-12% of wind turbine cost. The reliability of switching device play important role because failure of any converter may partially shut down and increase downtime of the whole wind turbine system which results in loss of million dollars investment. The power converters should produce low THD level (around 5%) and provide reactive power compensation support during fault condition. The efficiency of power converter is substantially affected by switching power loss which can be reduced by choosing efficient switching techniques and optimal arrangement of converters [13,12].

Back-To-Back Power Converters Topology

There are many types of power converter Topologies configurations which have been developed by manufacturers of power electronics industries for wind energy system [26]. One of them is back-to-back (BTB) connected power converters configuration which use two identical power converter units on both sides of common DC-link i.e. the generator-side and grid-side. The BTB converters configurations can be used in the many commercial WECS as summarized in above Figures. This back to back connected converters configuration maintained the bidirectional power flow from variable voltage/frequency (generator side output) to fixed voltage/frequency (grid-side output) and vice versa.

As the power flow is bidirectional so it can be used with any of the generator like SCIG, DFIG, PMSG, and WRSG [58,38].

IV. METHODS FOR FRT AND LVRT COMPLIANCE

The fault ride through (FRT) in Type 3 and 4 wind turbines and wind farms system can be accomplished inmany ways. But, the big challenge is to manage the surplus energy during grid faults, so many methods have been introduced in last few decades as follows:

(i) Pitch control method to regulate the active power generation.
(ii) Use different control techniques at wind turbine, DC link and power converter level.
(iii) Dissipation of surplus energy in the DC-link by using chopper techniques, ac crowbar, and braking resistor.
(iv) Use of compensation devices.
(v) Storage of surplus energy in the dc-link by using some external energy storage systems like fly wheel, battery bank, super capacitor/ELDC ultra capacitor bank.

During grid fault, the WECS requires to feed necessary reactive power to grid fault and simultaneously need to either store the excess active power or dissipate it through some electrical circuit. Instead of dissipating the active power it must be stored in some energy storing elements. So for this purpose energy storage elements must possess some desirable features as follows: it must have fast response characteristic and flexible energy management. In the past few years, some of energy storage elements have been utilized like batteries, flywheels, conventional capacitors and ELDC ultra-capacitor. All these electrical elements provide energy storage solutionsunder various conditions. Batteries are always a costly affair due to it fixed short life cycle, regular maintenance requirement and high replacement cost. Moreover, their slow state of charge is always difficult task to handle. Flywheels are generally very large in size in order to accommodate and store huge power during fault. The installation and maintenance of flywheel are big issue because it required numerous safety measures. The Supercapacitor/ELDC ultracapacitor is a cost-effective solution under these situation and coming out with emerging option in the area of energy storage systems. So the supercapacitor/ultracapacitorable togive a high power density alongwith fast rate of charging/discharging capabilityover wide temperature range [37,45,7,28].

V. ROLE OF WIND FARMS IN ELECTRICAL SYSTEM

A wind farms comprises a group of wind turbines which are used for the wind power generation in different ways. Earlier, most of the wind farms have been installed on land due to low initial and maintenance costs. But in recent years, there is lots of advancement has been happened in high power wind turbine technology. As a result of that the offshore wind farms are gaining more attention due to large power generation capability under strong wind speed [48].

This grid connected wind farm consists of many off-shore WECS units which are installed at different locations for optimum power generation. The whole power generated by all the WECS units will be collected at offshore PCC and transmitted via a transmission line at MV/LV levels. This electrical power is further transmitted at higher voltage level via a long HVAC transmission line and feed into the on shore grid. So, there are lots of wind farm arrangements to collect the whole powers from large number of off-shore wind farms are transmitted from off-shore to on-shore by using HVAC transmission line [4, 15].

VI. COMPARISONS OF DIFFERENT WECS CONFIGURATIONS IN WIND FARM

The comparative study of all kinds of WECS is compared with respect to different types of generator and power converters usedin various configurations. It also include various option available such as utilization of power convertercapacity, speed-range, gearbox requirement, external/internal reactive power compensation, maximum power point tracking (MPPT) ability; wind turbine technology and fault ride-through compliance requirement etc. as shown in table 6.1.On the basis of above parameters the Type 3 turbines (DFIG) and type 4 turbines hold the highest penetration in today's market and this technology have been used by most of the manufacturers. Due to feasibility of direct drive option, most of the future projects are of Type 4 (PMSG/WRSC) technology in recent the scenario [36,6,16].

Table 6.1: Comparison of Different WECS Configurations

System	Fixed Speed	Semi-Variable speed		Full-variable speed	
Generator type	SCIG	WRIG	DFIG	SCIG	WRSG/ PMSG
Converters Topologies	none	Diode and Chopper	Direct single-stage/ Indirect two stage	Direct single-stage/ Indirect two stage	Direct single-stage/ Indirect two stage/ Indirect three stage
Converter capacity utilization	10%	30%	30%	100%	100%
Rotor Speed	±10%	±30%	±30%	0 to ±100%	0 to ±100%
Gear box Stage	3	3	3	3	3/2/1/0
MPPT ability	no	limited	yes	yes	yes
FRT Capability	By external circuit	By external circuit	By power converters	By power converters	By power converters
Need External Reactive Power Compensation	yes	yes	no	no	no
Capacity of Wind Turbine	1.5MW	2.0MW	6.0MW	3.5MW	7.5MW
Market position/ Status	Few/ outdated	Few/ outdated	1st Highest/ highly mature	Few/ Emerging	2nd Highest/ mature

VII. CONCLUSIONS

This paper has given the brief outline of the recent research happening around the world in the field of wind energy system. It is mainly focused on various types of grid connected generators and power converters topologies under different operating conditions (Table 6.1) for onshore/offshore wind farm. An attempt to make a viable solution for extraction of maximum power from wind through different control schemes so that system become more efficient and cost effective .Like for offshore wind farm system, a high torque low speed operation is required at a very high power rating with minimum maintenance cost. Therefore direct drive permanent magnet synchronous generator with back to back converter topologiesmay bebetter solutionfor these kinds of applicationsand their control issues are not so much complicated in comparison to other configurations.

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