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Comparative Study of Different Grid Connected Wind Energy Conversion System Configurations

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Abstract

As per the present scenario of the world energy crisis, Renewable energy conversion systems (wind energy) have become the most prominent alternative in the field of renewable energy, especially at offshore locations due to the availability of wind in huge amounts round the clock. This paper summarizes the comparative study of most commonly used generators and power converters configurations at off-shore/on-shore wind farms. A comparison study has been done on the basis of their fixed/variable speed operation, MPPT ability, FRT ability, power converter utilization, power factor, reactive power compensation, with and without gearbox, and other technical parameters.

Keywords

Wind Energy Conversion Unit (WECU), Fixed Speed Wind Energy Conversion Unit (FSWECU), Squirrel cage induction generator (SCIG), Doubly Fed Induction Generator (DFIG), Permanent Magnet Synchronous Generator (PMSG), Maximum power point traction Technology (MPPTT)

1. Introduction

In last few decade years, the renewable energy sources especially wind energy emerged as a best replacement of fossil fuels/nonrenewable sources due to several issues as given below:

- Limited availability
- Globally abrupt & high price risk
- Environmental pollution issue
- Global warming etc.

So, we are more attentive to produce electricity by all the renewable energy sources like wind, hydro, tidal, geo-thermal, solar, sea waves and biomass sources etc. Now a day, a lot of research works in progress in the field of NCER i.e. on renewable energy for power extraction and production. Out of all renewable sources, the wind energy is one of the best promising area among the renewable energy sources due to easy and free availability of the wind in bulk for throughout the year in any area. There are several other reasons also by which we are shifting towards wind like availability in bulk amount, competitive cost, clean and eco-friendly environment & power generations etc. So, research in this area is going on with high peaks. It makes a place in the heart of manufacturers which can be seen from its exponential industrial growth as a result turbine manufacturing industry as well as the bulk power consumers market are in demand because of cheap and clean wind power generation [11, 14].

Global cumulative installed capacity has explosively increased day by day in year 2017-18 it increased from 23.8 GW to 539.6 GW. As per the current growth rate in year 2019-20 it expected up to 760 GW. There was a sudden rise in electrical power demand among those countries that are looking for alternate pollution free electrical power & make their country rich in the field of energy.

As per the different studies 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. Different comparative studies are also shown by the histogram graph given in figure 1 & 2. These pictures clearly indicate the bright future of off- shore wind power across the world. Abruptly increment in installation capacity of wind plants i.e. from 4.1 GW to 18.8 GW are also studied by histograms (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 [36]. The design, size, locations and type of offshore wind turbines play very important role for maximum wind power extraction & generation of power. 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 & have great significance [31-38].

2. Literature Survey

Hristiyan Kanchev et al. [1], Georg Hille et al. [2], OKA Heinrich Wilk et al. [3] and R. Messenger et al. [4] discussed the basic ideas of Photovoltaic cell and develop a Micro grid for different applications. Chapin et al. [5] presented the role of semiconductor materials in the renewable energy. Hohm, et al. [6], Hussein et al. [7], Koutroulis et al. [8], Eftichios Koutroulis et al. [9], M. Veerachary et al. [10] and I. S. Kim et al. [11] have investigated and proposed various method for the operation of Photo Voltaic cell. A PV module can produce electric power at a point, called an operating point, anywhere on the I-V curve. The coordinates of the operating point are the operating voltage and current. There is a unique point near the knee of the I-V curve, called a maximum power point (MPP), at which the module operates with maximum efficiency and produces the maximum output power. J. A. Gow et al. [12], I. H. Altas et al. [13] and I. S. Kim et al. [14] discussed different method to develop photovoltaic array. Mohamed A. H. El-Sayed et al. [15] presented the working of solar cell and array. E. Santi et al. [16], D. Franzoni et al. [17], Adel M. Sharaf et al. [18] and M. Tanrioven et al. [19] presented the stand alone working of fuel cell at different loads. Y. M. Chen et al. [20] have presented the working of hybrid system. J.J. Brey et al. [21], B. Ozpineci et al. [22] And O. Wasynczuk et al. [23] have presented the role of look-up table in the field of renewable energy. K.Wang et al.[24], S. Jang et al.[25], H. Matsuo et al.[26], H. Matsuo et al.[27], F. Caricchi, et al.[28] and M. Marchesoni et al.[29] worked on a circuit technique that reduces the boost-converter losses. Here, unregulated DC input into a controlled DC output at a desired voltage level. Y. Song et al. [30], A. M. Tuckey et al. [31], L. Solero et al. [32], G. K. Andersen et al. [33] and H. Ertl et al. presented the working of inverter with MOSFET technology. A. Kotsopoulos, et al [34], N. Ashari et al. [35] and C. V. Nayar et al. [36] Ziyad M. Salameh et al. [37] and J. Larminie et al. [38] have made a comparison of the three-phase load connected with renewable sources.

3. Grid Connected Wind Energy Conversion System

On account of conversion system of wind turbine, we compare two things one is mechanical and other one is electrical components. Under the influence of these two systems, it works properly under dynamic conditions. The mechanical system is used to capture wind power efficiently with the help of properly designed aerodynamically shaped rotor blades and copters which is coupled with electrical generator i.e., Induction machine via a common mechanical shaft with gear arrangement.

There is a simple conversion of mechanical power into electrical power with the help of induction machine .i.e. the common mechanical shaft is used to transmit mechanical power extracted from wind turbine to generator which further converts this mechanical power to electrical power [18, 27, 28, 37]. Now by using suitable power step up transformers and filters circuits and then this electrical energy transferred to grid at desirable grid voltage and frequency as shown figure 3 & grid behave as a common station of electricity.

3.1. Mechanical strength related with turbine

- 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
- The rotor blades (Used to convert the wind kinetics energy into mechanical energy)
  - shapes and angle of blades
  - wind density
  - wind velocity

With the help of Pitch and yaw control, wind turbine may generate maximum mechanical energy efficiency at the given range of rated wind speed for that particular area. Two mechanical systems with different torque-speed characteristic can be coupled with the help of multistage gearbox system as shown in figure. 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 etc. 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 as we discussed [24, 25].

3.2. Electrical strength related with turbine

Electrical system converts the mechanical power into useful electrical power and transfers the same at grid. The Electrical system of WECS composed of many components like:

- Generators
- Transformers
- harmonics filters
- DC link elements
- power converters
- cables
- Load

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 of electricity.[8].

In present time synchronous Generators are used in low speed due to feasibility of large number of poles. The stator windings of synchronous generators can be designed for any number of poles and size at variable wide range of speed (Speed: low, medium, high) which not possible in Induction generators so induction generators are out of use now. The power electronics converters (Thyristor, Mosfet, SCR) interfacing between generator and grid through DC-link capacitors & filter circuits, transformers and harmonics filters may provide many types WECS configurations depending upon grid synchronization parameters like frequency etc. In many configurations, transformers can be optional because sometimes the grid side inverters are able to operate at grid voltage to make the system easy [1, 36].

4. Control System

Wind energy conversion system (WECS) mainly consist of two parts one is mechanical and other is electrical. These always require some control systems in order to achieve the desirable dynamic and steady state performances of the system. Here, the dynamic and steady state performances of WECS are monitored by filters & controllers which are usually implemented for the switching purpose at generator-side and grid-side inverters.

Electrical & Mechanical parameters are as follows:

- Rotor speed
- Rotor blade angle and yaw angle
- Generator voltage
- Current
- DC-link voltage
- Grid & frequency

5. Fixed and variable speed control based WECS Configurations

Now in present scenario of world, there are so many wind turbines topologies available in the world for commercial for fixed speed as well as for variable speed. WECS configurations with different kind of generator sets are as follows:

5.1. Fixed speed control based WECS Configuration

This configuration is called fixed speed control WECS because generator speed varies around only 1 to 2 % only at variable wind speed as shown in figure 4. This concept-based configuration of WECS 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 and filter circuits [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 at that place. The SCIG further delivered this power to grid at desired frequency 50Hz/60Hz (depends upon country to country generation) through the soft-starters and step-up transformer & other related technologies.

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 electrical faulty condition, wind speed variations reflection in grid [22, 25, 32]. The fixed speed turbine WECS configurations are still in operation and available in MW range to generate the electricity.

5.2. Variable speed control based WECS Configurations

The variable-speed based control operation increases the overall conversion efficiency and minimizes mechanical stress on the components of wind turbine. As a result of which increased the life span and cycle of equipment due less wear and tear with minimum requirement of maintenance running and annually caused by wind gusts. [25, 28, 38].

5.3. Semi-Variable control based WECS Configuration

There are mainly two kinds of semi-variable based WECS:

- WRIG
- DFIG

These are shown in figures 5 and 6. 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. optimum slip control method [5, 33, 34, 37].

In DFIG based WECS power is transferred from wind turbine to grid through both stator as well rotor winding of generator as shown in figure 5. 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 25 to 30 % of its rated speed which enhance its conversion efficiency and dynamic performance and make the system easy & comfort [29, 32].

Drawback:

- Speed range
- High turbine cost
- Rotor circuit power loss
- Complex control strategies
- Regular maintenance for gear box and slip ring
- Frictional loss and high noise etc.

5.4. Full-variable control based WECS Configuration

Types of full-variable control WECS:

1. SCIG
2. WRSG
3. PMSG

WECS configurations along with power converters up to their full load capacity are shown in figures 8. These WECS configurations are fully decoupled and capable to deliver the electric power to the grid at full range of its rated speed i.e. generally in rpm (efficiency: 0% to 100%). Moreover, there is no need of soft starters to run it. Power converters are use to deliver the required reactive power compensation for grid FRT compliance [3, 23, 25] to remove the reactive effects. The synchronous generators have two types of rotor either electrically excited field windings (WRSG) or permanent magnet (PMSG).

1. WRSG
2. PMSG

But in case of 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 7 and 8. This WRSG based configuration can be possible either by using a gear box system or without a gear box system which is also known as a direct drive system. The purpose of multistage gear box system to match the speed difference between both generator and turbine speed and this process is known as speed matching or rpm matching [9].

On the other hand, at higher rotor speed, WRSG is quite good option with multistage gearbox system but when system demands low speed operation then WRSG becomes a costly affair because it require machine with large no. of poles or other modifications. In order to accommodate large number of poles machine with a big DC excitation system increase its size, volume, weight and cost. So, a big size of tower, materials and foundation required to withstand these machines which in turn increase the overall cost of the WECS installation. 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 in current scenario in wind system.

5.5. Direct-Drive control PMSG based WECS Configuration

Rotor speed is the main difference between multistage gear-drive system and direct-drive system of wind turbines. The direct drive based WECS deliver power at a low speed. The shaft of generator rotor is directly coupled with the turbine rotor as shown in figure 9. After studying several research articles about generators, it is finding out that the synchronous generator based WECS have good mechanical capability for direct-drive wind turbines and there is no need of gearbox system to convert speed [17]. Here, the rotor of synchronous machine is directly coupled (mechanically) with wind turbine system through a common shaft at a low speed so that we can extract power at low speed. This feature of synchronous generator will increase the life span of the system with minimum requirement of maintenance from installation to run.

6. Different Power Converters Topologies

In Wind Farm On the basis of electric power conversion strategies, the power converter topologies are mainly classified in two ways as Direct and Indirect topologies. Now see the different topologies:

1. Direct conversion with single-stage AC/AC conversion.
2. Indirect conversion with two-stage (AC/DC and DC/AC) conversion.
3. Voltage Source/Current Source half and full controlled converters with or without DC link, passive controlled converters
4. Indirect conversion uses three-stage (AC/DC and DC/DC and DC/AC) conversion

- **Special Features**

  There are some special features in the selection of choosing power converters topologies in WECS like:

  ➢ Initial cost which is generally 5-12% of wind turbine cost.

  ➢ Reliability of WECS.

  ➢ Power converters (which are used to reduce THD level (around 5%).

  ➢ Power compensation support system.

  ➢ Back-To-Back Power Converters Topology:

- **Methods for FRT and LVRT Compliance**

  Surplus energy demand during grid faults, to overcome with this problem the fault ride through (FRT) is come in action. Several methods have been introduced in last few decades as follows:

  - Pitch control method to regulate the active power generation.
  - Use different control techniques at wind turbine, DC link and power converter level.
  - Dissipation of surplus energy in the DC-link by using chopper techniques, ac crowbar, and braking resistor.
  - Use of compensation devices.
  - 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.

When fault occur at grid side, the WECS requires feed necessary reactive power to grid and simultaneously needing 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 solutions under 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 Super capacitor/ELDC ultra capacitor is a cost-effective solution under these situations and coming out with emerging option in the area of energy storage systems in this field [7, 28, 35, 37].

- **Role of Wind Farms in Electrical System:**

  It is a comparative study of wind farms as shown in table no. 1 i.e.

  - SCIG
  - WRIG
  - DFIG
  - SCIG
  - WRSG/PMSG

- **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 rating and power converters system and efficiency in various configurations. It also includes various option available such as utilization of power converter capacity, speed-range, gearbox requirement, external/internal reactive power compensation, maximum power point tracking (MPPT) ability; wind turbine technology, efficiency and fault ride-through compliance requirement etc. as shown in table on.1.

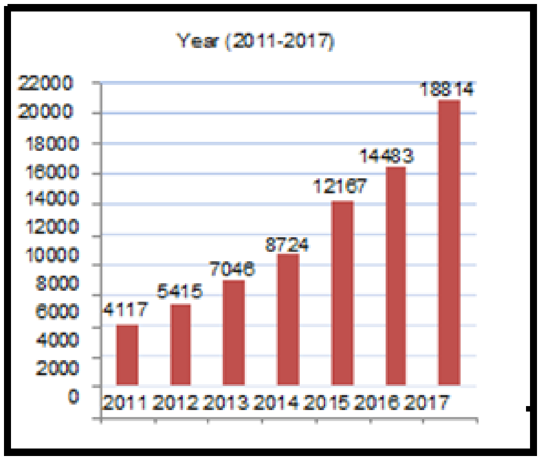

Figure. 1 Installed Wind capacity in MW (Market trends)

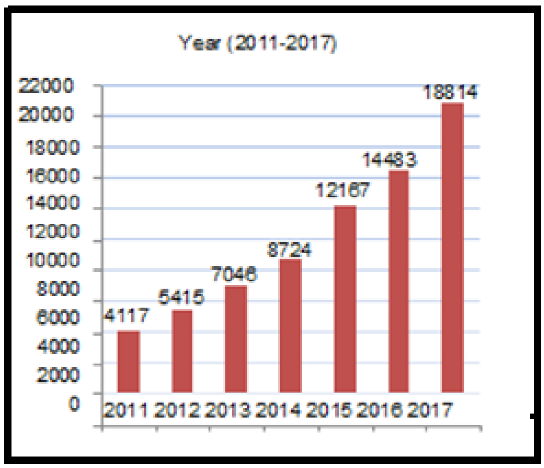

Figure. 2 Installed Wind capacity in MW (Market trends of offshore)

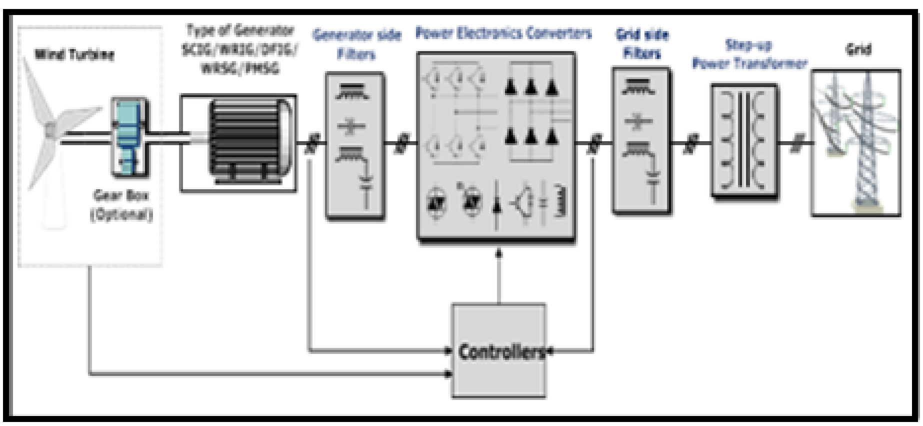

Figure. 3 General model of grid connected WECS Mechanical System

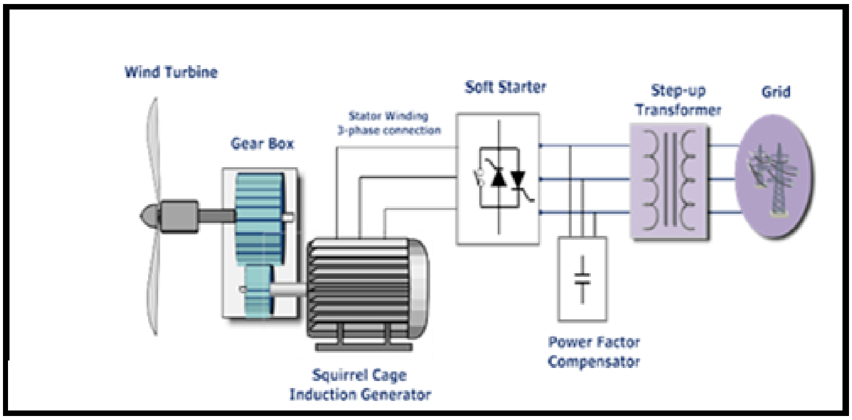

Figure. 4 Fixed speed control SCIG based connected WECS

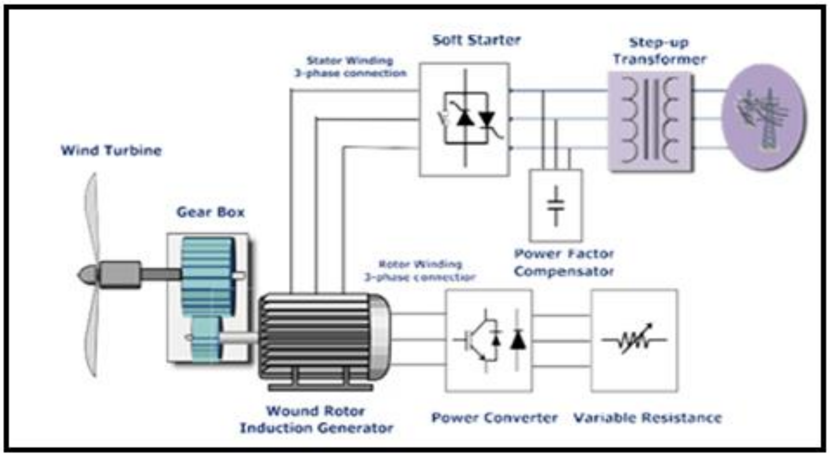

Figure. 5 Semi variable speed control WRIG based grid connected WECS

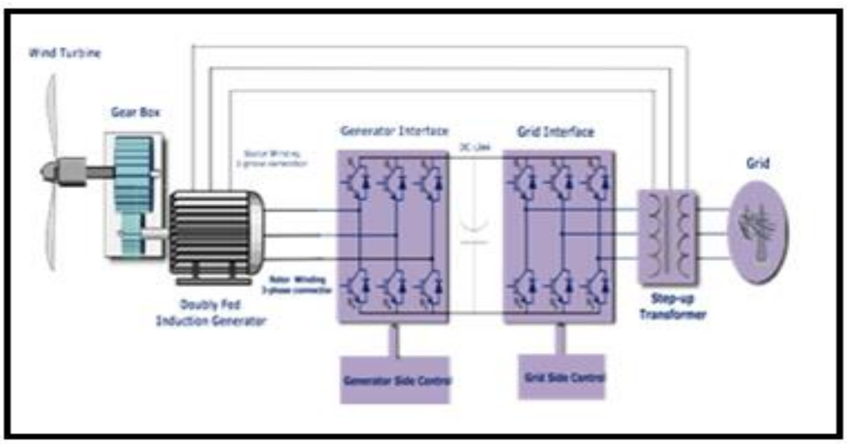

Figure. 6 Semi variable speed control DFIG based grid connected WECS

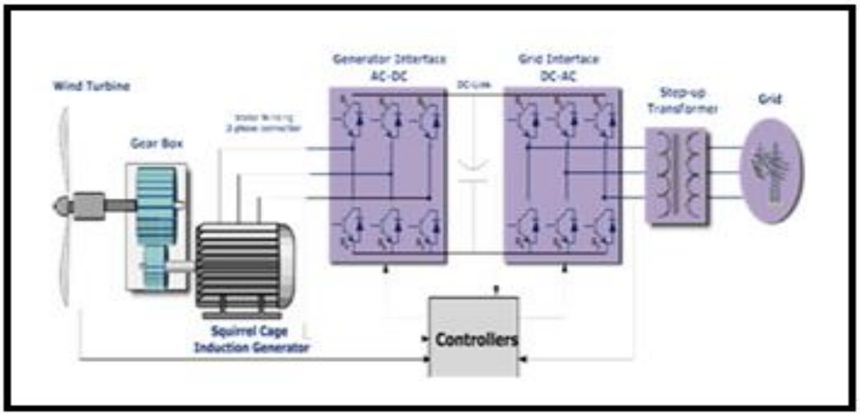

Figure. 7 Fully variable speed control SCIG based grid connected WECS

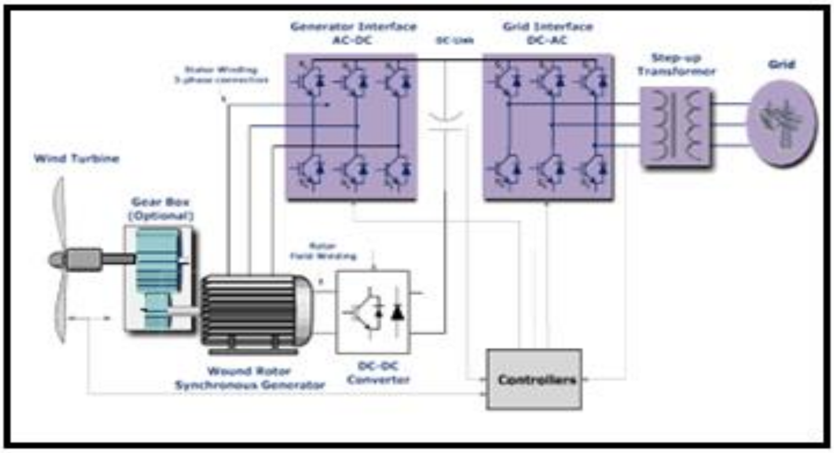

Figure. 8 Fully variable speed control WRSG based grid connected WECS

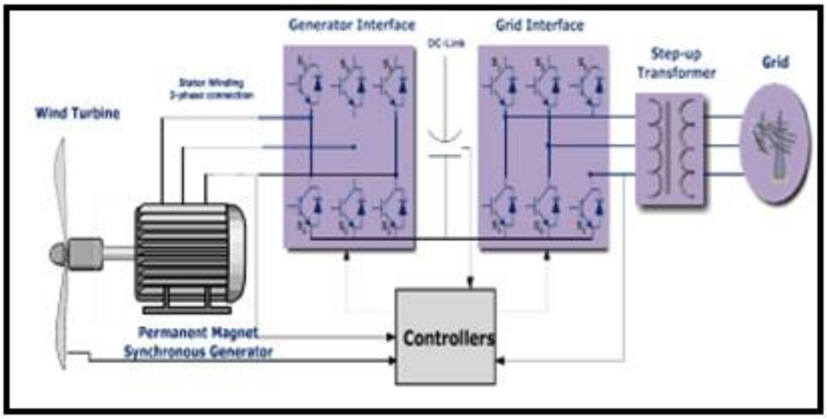

Figure. 9 Direct driven fully variable speed control PMSG based grid connected WECS

Table 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/three stage
Converter capacity utilization	10%	30%	30%	100%	100%
Rotor speed	±10%	±30%	±30%	0 to ±100%	0 to ±100%
Gear stage box	3	3	3	3	3/2/1/0
MPPT ability/ FRT capability	no (By extern al circuit)	limited	yes (By power converters)	yes (By power converters)	yes (By power converters)
Need External Reactive Power Compensation	yes	yes	no	no	No
Capacity of Wind	1.5 M W	2.0 M W	6.0 M W	3.5 MW	7.5 MW
Turbine (Market position/ status	Few/outdated	Few/outdated	1st highest/highly mature	Few Emerging	2nd highest/highly mature

7. Conclusion

By this paper the brief outline of the recent research happening around the world in the field of wind energy system is clear. It is mainly focused on various types of grid connected generators and their power responses i.e. converting topologies under different operating conditions as shown in table 1.

Location is as 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 becomes more efficient and cost effective & may adoptable in daily life. Like for offshore wind farm system, a high torque low speed operation is required at a very high-power rating with minimum running & maintenance cost. Therefore, direct drive permanent magnet synchronous generator with back to back converter topologies may be better solution from other kinds of application. Control technology is not so complicated in comparison to other configurations of wind farm.

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