Evolution of wind energy conversion system and recent challenges in grid integration: A review

Tomson Thomas$^{1}\ast$, Prince A.$^{2}$

$^{1}$Research Scholar, $^{2}$Associate Professor, Department of Electrical Engineering, Rajiv Gandhi Institute of Technology, Kottayam, Kerala, India 686501.
E-mail: tomsonpala@gmail.com

Abstract. The global demand for electrical energy is expanding twice as quick as the demand for primary energy. Highly reliable and fine quality power are demanded in the present-day power system scenario. Distributed generation including wind turbines and solar photovoltaic systems are significant in the perception of green energy. Electricity generation with renewable power generators like wind and solar are preferred to avoid $CO_2$ emissions. In the sustainable alternatives, wind energy is considered as one among the fastest evolving energy resources. The percentage of renewable energy in the worldwide generation increases day by day. In this paper, evolution of various wind energy conversion systems (WECSs) with their benefits and demerits are addressed. The increasing entry of power electronic converter (PEC) based renewable energy is transforming power system dynamics with new stability concerns. Several challenges like power quality issues, low voltage ride through (LVRT) capability, fault ride through (FRT) capability, power oscillations, primary frequency regulation (PFR), virtual inertia support etc in power system with the inclusion of wind energy are also discussed.

Keywords: Renewable energy, wind energy conversion system, maximum power point tracking, primary frequency regulation

1. Introduction

The inclusion of sustainable energy in power system introduce various technical confrontations like voltage stability issues, flicker, harmonic distortion etc. Nowadays, the electrical power generation from renewables like wind, is having more importance because of environmental perspectives and shortage of traditional fossil fuel based energy sources.

The contribution of renewable energy in the electricity generation is extremely significant due to the truth that they are bountiful in nature and inoffensive to the environment. The progress of WECS is very momentous in the inclusion of renewable energy in power system. Figure 1 shows that total worldwide installed capacity of wind energy in December 2017 is 539,581MW [1]. According to Global Wind Energy Council (GWEC), top five countries had greater than 20GW of established capacity including China (188GW), United States of America (89GW), Germany (56GW), India (33GW) and Spain (23GW). In India, 19% of total electricity generation is with renewable energy having a capacity of 63GW. Figure 2 shows the cumulative installed wind energy in India [2]. An installed capacity of 175GW using renewable energy is targeted by the Government of India by 2022 which includes 100GW of solar power, 60GW of wind power, 10GW of bio-power and 5GW of small hydro-power capacity [3].

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The presence of PEC in renewable power generators has utmost difference with conventional
Figure 1. Wind energy installed across the world [1]

Figure 2. Wind energy installed in India

synchronous generators. The active and reactive power flow control, maximum power point tracking (MPPT) and power quality are the considerable aspects to be analysed in the grid connected operation. The various challenges of wind energy systems connected to the power system are LVRT capability, FRT capability, frequency stability, virtual inertia support etc.

This paper concentrates on the evolution and recent challenges in grid integration of WECSs. Basic principles of wind energy is addressed in Section 2. Various categories of WECSs with their fundamental principles are elaborated in Section 3. In Section 4, various challenges incorporated with the grid integration of WECSs are investigated. Conclusions and research aspects are addressed in Section 5.

2. Basic principles of wind energy

Kinetic energy present in the wind is transformed into mechanical energy by wind turbines. Kinetic energy of the wind rely on air density and wind velocity. The wind power developed by the turbine is stated by

\[ P_w = \frac{1}{2} \rho AV^3 C_p(\lambda, \beta) \]  

where \( C_p \) is the power coefficient, \( \rho \) is the air density (1.225 kg/m\(^3\) at STP), \( A \) is the blade area of turbine in m\(^2\), \( V \) is the velocity of wind in m/sec, \( \beta \) is pitch angle of the blade, \( \lambda \) is the tip speed ratio (TSR).
The power coefficient, $C_p$, gives the ratio of wind turbine kinetic energy to mechanical energy. No wind turbine can transform greater than 59.3% of wind kinetic energy into mechanical energy by rotating a rotor as per Betz Law. The power coefficient depends on the blade pitch angle, $\beta$ and TSR, $\lambda$. TSR is the ratio of turbine blade linear speed to the wind velocity. Tip speed ratio is given by,

$$\lambda = \frac{R\omega}{V}$$

where, $R$ is the radius of turbine rotor in metre and $\omega$ is the rotational speed in rad/sec. The power coefficient is given by,

$$C_p(\lambda, \beta) = \frac{1}{2} \left( \frac{98}{\lambda_i} - 0.4\beta - 5 \right) \exp\left(\frac{-16.5}{\lambda_i}\right)$$

where,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.089} - \frac{0.035}{\beta^3 + 1}$$

The variation of power coefficient corresponding to TSR for different blade pitch angles is shown in Figure 3 [4]. The power developed and the maximum power point (MPP) are different for various wind speeds for a wind turbine as indicated in figure 4 [4]. The maximum power can be tracked by controlling generator speed for varied wind velocities.

### 3. Evolution of wind energy conversion system

In this section, various types in the evolution of WECS are discussed. Wind has been used for sailing of ships and pumping water. Earlier, wind turbines were utilized for grinding or milling grain and they were called windmills. Electricity was generated initially using wind turbines at Denmark in 1890. WECSs are classified into fixed and variable speed systems.

#### 3.1. Fixed speed wind energy systems

Fixed speed WECSs consist of a grid connected self-excited induction generator which is started as a motor using soft starter [5]. It can run as a generator in grid connected mode and the reactive power requirement is supported by shunt capacitors. This is treated as fixed speed WECS due to the reason that variation in shaft speed and operating slip of induction generator are not so much with the change in wind velocity. The conversion efficiency is very less for fixed speed WECSs.

#### 3.2. Variable speed wind energy systems

Variable speed WECSs are incorporated with a PEC to operate at MPP for varying wind speeds. Variable speed systems are classified as systems with fully rated converter (FRC) and reduced rated converter (RRC). Fully rated converter based system is normally employed with permanent magnet synchronous

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**Figure 3.** Power coefficient Vs TSR for different pitch angles [4]

**Figure 4.** Maximum power point tracking of wind turbine[4]
generator (PMSG) for recent wind energy extractions. The generator speed is dissociated by using power electronic converters. The output will be variable voltage and variable frequency, subjected to the wind velocity. The major demerit of WECS using PMSG is that it requires a PEC with a rating equal to the generator.

WECSs with reduced rated converter includes doubly fed induction generator (DFIG) which is extensively used in large scale applications. The main benefit of DFIG is its aptness to run as generator in sub synchronous and super synchronous speeds. Its PEC rating is only one third of the generator rating. Controls are possible through rotor side converter (RSC) and grid side converter (GSC). The operating principle of DFIG is based on injecting three phase currents of variable amplitude and frequency into the rotor to allow the operation under different rotor speeds to achieve peak wind power extraction with optimum value of power coefficient. In sub-synchronous mode of operation, active power flow will be from stator to utility grid and from utility grid to the rotor. But in super synchronous operation, the real power flows from stator and rotor to the utility grid.

4. Recent challenges in wind energy conversion systems

Wind power plants (WPPs) are operated with PECs whereas conventional generating stations with synchronous generators are straight away connected to the grid. Wind turbine input is uncontrollable and it fluctuates stochastically. Wind resource assessment studies are very relevant in finding the optimum location to extract maximum wind power.

Extraction of maximum power for a location at different wind speeds by controlling the generator speed corresponding to the optimum TSR is a challenging task. MPPT technique in a PMSG based WECS connected to the network using optimum speed and wind speed with a fast controller is established in [6]. Attempt has been made with different methods of MPPT algorithm using fixed and variable step size for a small-scale WECS and are compared with fuzzy logic and the look-up table indirect methods in [7]. An adaptive MPPT algorithm for fast tracing of MPP under fast varying wind conditions for a WECS is discussed [8]. A new MPPT approach for WECS with PMSG depending on rectified dc voltage and current is discussed in [9]. A rapid tracking MPPT algorithm using matrix converter for a WECS is analysed in [10]. In [11], a comparison of WECS with a maximum electrical power tracker (MEPT) and maximum mechanical power tracker (MMPT) for the extraction of maximum electrical power and maximum mechanical power respectively. An MPPT strategy for WECS with DFIG using a Lyapunov-based analysis is discussed in [12]. Sensorless control of a grid interfaced DFIG based WECS for MPPT capability and power smoothing using a rotor position estimation algorithm is discussed in [13].

In fixed speed WECSs, fluctuations in wind are directly conveyed to the alterations in output power and it may produce flicker. In unfixed speed systems flicker will not be present due to decoupling of rotor and grid. An exhaustive control of a WECS is elaborated with a controller enhancing power quality using DC link capacitor and power converter in the absence of wind in [14]. Power quality troubles due to the grid connected WECS are addressed using IEC61400 and a STATCOM with battery energy
storage system (BESS) is adopted to enhance the power quality in [15]. A STATCOM and BESS control approach is employed for enhancing power quality and stability of a fixed speed WECS in [16]. A Takagi-Sugeno fuzzy model based linear quadratic regulator is employed for the mitigation of power quality issues of a wind-hybrid power system with BESS in [17].

If the percentage of variable speed wind turbines in the system is high and they disconnect at relatively small voltage reductions and a voltage drop may occur. Therefore wind turbines should have a FRT capability to endure during voltage drops for certain durations without tripping. Fixed speed WECs contribute to the network fault currents. DFIG based wind generators will lend to the fault currents but it may be disconnected from the network. WECSs with FRC do not donate to system fault current. Fault ride-through capability means WECSs should have an ability to remain connected to the network during fault and must contribute system stability. Crowbar protection converts DFIG to a squirrel cage induction generator for improving FRT capability. A DC-link controllable fault current limiter in RSC is suggested for improving the FRT capacity which abolishes the demerits of AC crow bar protection in [18]. LVRT means the proficiency of the generator to be connected to the network during a voltage sag. Resonant controllers are proposed for asymmetrical voltage sags in DFIG to enhance LVRT competence in [19]. Improving FRT capability of a DFIG with superconducting magnetic energy storage fault current limiter and RSC control is discussed in [20]. A control approach for the betterment of LVRT capability of DFIG using passive and active compensators are discussed in [21]. A virtual impedance control method for enhancing high voltage ride through (HVRT) capability of DFIG during voltage swell is analysed in [22]. A genetic algorithm based LVRT control method for DFIG connected to the network is addressed in [23].

Voltage on a transmission network is determined chiefly by the interaction of reactive power flows. Fixed speed induction generators absorb reactive power to maintain their magnetic field. Voltage of the network can be supported by using shunt capacitors to reduce the reactive power drawn from the network. Variable speed WECs can control the reactive power to improve the voltage of power system. Reactive power and voltage control can be achieved by using reactive power compensators such as static var compensator (SVC) and static synchronous compensator (STATCOM). A direct torque and reactive power control of grid connected DFIG with a matrix converter is discussed in [24]. In [25], enhancement of transient voltage stability of grid tied DFIG based WECS by controlling superconducting fault current limiter and reactive power is discussed. A changeable reactive current to voltage idea of a DFIG for voltage regulation of a WPP is addressed in [26].

Reactive power control of DFIG based WPPs for the damping of power system oscillations is analysed in [27]. Power system oscillation damping can be attained by controlling the active power of BESS and reactive power modulation of line side converter in [28]. Control of WECS with DFIG and power system stabilizer for power oscillation stabilization under uncertainties in power system is addressed in [29]. Design of controllers for power oscillation damping of WPPs with DFIG are discussed in [30]. Various aspects on sub-synchronous oscillation in series compensated power system with WPPs are discussed in [31,32].

Because of the presence of PEC, the generator inertia is decoupled from the grid. Virtual inertia is needed for the WECS to take part in the frequency regulation. Frequency support can be furnished by a WECS to the power system by increasing the power at the instant of requirement. It can be attained by de-loading the wind turbines from the MPP and hence by creating a margin for the frequency control. Primary frequency regulation using variable droop for de-loaded WECS are discussed in [33]. Virtual inertia technique and optimized power point tracking for a DFIG based WECS are analyzed in [34].

5. Conclusions
In this paper, a comprehensive review is done on the evolution of WECS. The various challenges of WECSs connected to the power system such as MPPT, power quality issues, FRT capability, LVRT capability, reactive power support, voltage stability, power oscillation damping, primary frequency regulation and virtual inertia support are discussed. Design of better controllers are required for the
WECSs to enhance the dynamic behaviour in power system.

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