A Comprehensive Review on Wind Energy System for Electric Power Generation: Current Situation and Improved Technologies to Realize Future Development

Devashish*‡, Amarnath Thakur**

*Department of Electrical and Electronics Engineering, Research Scholar, NIT Jamshedpur, India-831014

** Department of Electrical and Electronics Engineering, Professor, NIT Jamshedpur, India-831014

(devashish.sit@gmail.com, anthakur1@gmail.com)

‡ Corresponding author: Devashish, NIT Jamshedpur, India-831014, Tel: +918877031331,

devashish.sit@gmail.com

Received: 04.04.2017 Accepted:16.07.2017

Abstract- In recent years, interest has risen in renewable energy (RE) sources particularly wind energy for the generation of electricity. The researchers have made several attempts to find the solution for effective utilization of wind energy. Following the consequence of comprehensive study and extensive research on the topic, wind energy is now vastly exploited renewable energy source to produce electricity. The main challenge for wind energy conversion is to cope with erratic nature of wind. The paper seeks to present a review of wind energy conversion system (WECS), highlighting its electrical and control aspects, including short notes on aerodynamics and mechanical features. Capacity of wind power installation of the world including India is shown and discussed. The paper investigates the latest associated technology with wind electrical system and future research direction.

Keywords Wind energy conversion system, Power converters, Pitch control, Maximum power point tracking, Energy storage.

1. Introduction

Wind energy system is becoming more and more popular due to technological development in recent years. In this situation wind energy is going to be a better option to fulfil the ever increasing demand of energy. It is the cleanest form of energy having no emission which is detrimental to the environment. Utilization of wind energy is mostly associated with conversion into electrical energy. After the oil crises in 1973 European countries started to find solution for their own renewable energy [1].Among the known energy sources like wind, solar and biomass, wind energy for electrical power generation has shown the fastest rate of growth in recent years [2].

Wind energy conversion is the process by which physical energy of wind is converted into electrical energy. Wind possesses kinetic energy which is first converted to mechanical power by the help of wind turbine, and that mechanical power is used to create electrical power. Despite of the fact that wind turbine has some untoward environmental impact [3, 4], like noise, it is still more environment friendly when compared to fossil fuel. Due to excessive exploitation of conventional sources like coal, petroleum and natural gases for energy requirement, the emission of carbon dioxide is growing, that is expected to rise up to 36 billion metric tons globally in 2020 [5]. Due to rise of CO_2 in the atmosphere, the average global temperature could rise between 2^0F and 11^0F by year 2100 [6]. The solution of these serious environment related issue lies in the use of clean, long term eco-friendly renewable energy sources. Several countries have come forward for the development of technology so that effective exploitation of renewables like wind, solar, tidal, geothermal, biomass, could be done. Among all these existing renewable sources wind energy can be one of the most efficient energy source for the generation of power, having the ability to fulfil world's energy needs [7].

Due to consistent research towards the development of new technology for harnessing wind energy, the tremendous growth of wind power from the year 2004 to 2015 is shown in Fig. 1. In the year 2015, total of ~422 GW wind power generation was installed worldwide, with the increase of ~60 GW only in 2015 and it is aimed to reach ~760 GW in 2020 [8]. India plays a major role in the global wind energy market. It stands at fifth position worldwide having an installed capacity of ~ 25 GW [9]. Blessed with coastline of 7517 km, India has tremendous potential for the wind power generation, and much is to be done specifically in harnessing wind energy to achieve its full potential. A pie chart expressing share of wind energy among other renewables in India is shown in Fig. 2. Year wise rise of wind power installation capacity in Megawatt is depicted by Fig. 3.

2. Wind Technologies

Power generation with the help of wind energy is one of the most viable solution for fulfilling energy demand. Due to erratic nature of wind, its forecasting is one of the fundamental necessity in wind energy systems [10]. The utilization of wind energy can be done in two ways. It can either be directly used as mechanical energy or by converting it into electrical energy indirectly. Wind turbine is the vital part of WECS which is used to capture physical energy of wind and converting it to mechanical energy by rotating rotor of generator with the help of gearbox [11]. Production of electricity by exploiting the abundantly available wind energy became possible only after advent of wind turbine [12]. In the Fig. 4, a detailed view of the inside of a wind turbine, its components, and their functionality is shown. The development of special type of generators, together with the help of power electronic devices, have made the scope for gearless turbine designs [14].

2.1 Wind turbine design

A wind turbine is a complex electromechanical system consisting of many components and subsystems. Selection of size and design of wind turbine is done according to demand, location, and wind profile with the prime motive of reduction in price and maximizing wind energy capture. From the last many decades research and advancement for the turbine technology has been rising.

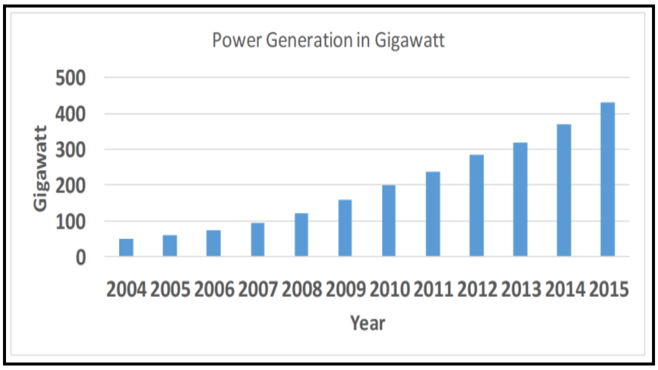

Fig. 1. The cumulative global wind power growth from the year 2004 to 2015.

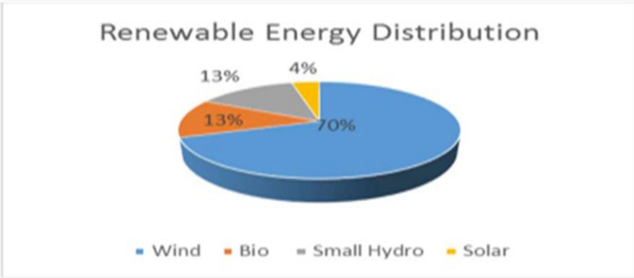

Fig. 2. Distribution of different renewable energy sources in India.

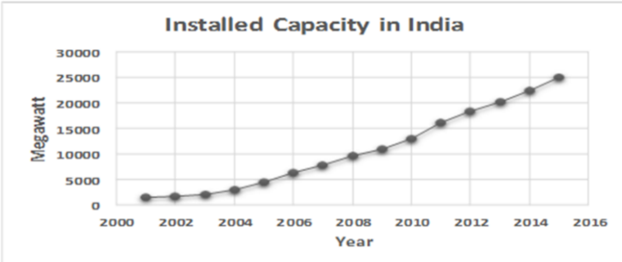

Fig. 3. Wind power growth in India.

As a result of continuous research and development, now wind turbine of rating varying from several kilowatts to megawatts is available. Super conductor based power equipment has been the subject of intensive research from the last two decades [15]. Due to the use of High temperature superconductor (HTS) technology, size and cost of 10 MW – class generator for wind turbine system is reduced [16]. The one of the most important parameter of the wind turbine is its diameter. Nowadays the emphasis is being given on turbine with long turbines blades, as longer blades have the capacity to sweep wind energy from a larger area and generate greater amount of output energy.

Wind turbines are mainly of two types: the horizontal-axis type model (HAWT), and the vertical-axis type model (VAWT) [17]. Due to their greater efficiency HAWTs are more preferred choice than the VAWTs in most of the wind industries. Despite of having lower efficiency in comparison to HAWTs, VAWTs are advantageous in the fact that it capture wind energy from any direction [18]. Moreover, it has lower cut in speed due to which it can generate electricity even in low wind speed. The VAWTs are mainly effective in small scale application such as on rooftop. In recent years, interest has risen towards exploitation of offshore wind resources [19]. Therefore, commercial development of floating horizontal axis wind turbines (FHAWTs) and vertical axis wind turbines (FVAWTs) is also increasing. A wind turbine typically consists of several components and subsystems like generator, rotor hub and blade, gearbox, and a tower. All the main parts of a wind turbine are explained below briefly [20, 21 123].

Rotor Hub and Blade- The interaction between wind and rotor blade is the important factor for the production of power. The rotor consists of large turbine blades and hub. Blades resemble the wings of an aeroplane. Blades are normally large in size. Generally three bladed wind turbines are used in practice. Another component of rotor is pitch drive, which is used to keep the rotational speed of rotor blades at desired operational range of 1000-3600 RPM (revolution per minute).

Gearbox- Gear and bearings are two main components of gearbox. The rotor speed in wind turbine (Variable speed wind turbine with pitch system) is ranging from 7-30 rpm and gear box ratio is typically of ratio 1: (100-150), for 6 pole generator rated RPM is 1000, 4 pole rated RPM is 1500, and for 2 pole generator RPM 3000. In general 4 or 6 pole generator is used with gear box. The rotor speed of wind turbine is not sufficient to produce electricity as most generators need the speed of 1000-3600 RPM. Therefore gearbox increases the speed of the generator rotor to 1000-3600 RPM to render generator functional.

Generator- The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity. Thus generator converts mechanical energy of wind turbine rotor into electrical energy.

2.2 Wind Aerodynamic Model

Air creates two type of dynamic forces when it flows over any surface, one is drag force (in the same direction of air flow) and another is lift force (in the normal to air flow).These two forces are responsible for generating the driving torque needed to rotate the turbine blades. The mechanical power P_{wind} of the wind can be expressed as [22].

$$P_{wind} = 0.5\rho\pi R^2 V_w{}^3 \tag{1}$$

Where ρ is the air density, R is the turbine radius in V_w is the wind speed and ω_r is the rotational speed of wind turbine. The power captured by the blades of the turbine, P_{blade} is

$$P_{blade} = 0.5\rho\pi R^2 V_\omega{}^3 C_p(\lambda,\beta) \tag{2}$$

where, λ is tip-speed ratio (TSR) and β is the pitch angle of turbine blade. C_p is the power coefficient. It is given by,

$$C_p(\lambda,\beta) = 0.5176((116/\lambda_i) - 0.4\beta - 5))^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{3}$$

λ_i may be expressed by the relationship,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

Tip-speed ratio (λ) is defined as ratio of angular velocity of turbine and wind velocity. It is given by,

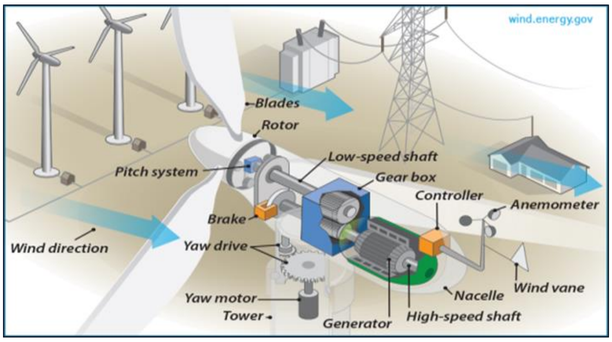

Fig. 4. Inside of a wind turbine [13]

$$\lambda = \frac{R\omega_r}{V_w} \tag{5}$$

Turbine mechanical torque (N-m) is given by,

$$T_m = 0.5\rho\pi R^2 V_\omega{}^3 C_p(\lambda,\beta)/\omega_r \tag{6}$$

On the basis of above written equations, a MATLAB program has been written to analyse the relationship between tip to speed ratio (TSR) and power coefficient at varying pitch angle as depicted in Fig. 5. It can be concluded that at lowest pitch angle value of turbine blade, power coefficient is maximum at given wind speed. It is evident that only one particular value of TSR yields the highest efficiency. It may also be verified from the figure that theoretical maximum power coefficient cannot exceeds a certain value 0.59(Betz limit). The graph between the power coefficients versus tip-speed ratio is very important tool in the characterization of converters used in wind electrical system.

3. Wind Energy Conversion System

Electricity is generated by converting physical energy of wind with the help of rotor. The kinetic energy of wind is captured by wind turbine with the help of especially aerodynamically designed blades. The mechanical energy of rotating blades is transferred to generator rotor and electricity is generated with the rotation of rotor. This electrical energy can be used to fulfil standalone demand or sent to grid through a transformer for more widespread applications.

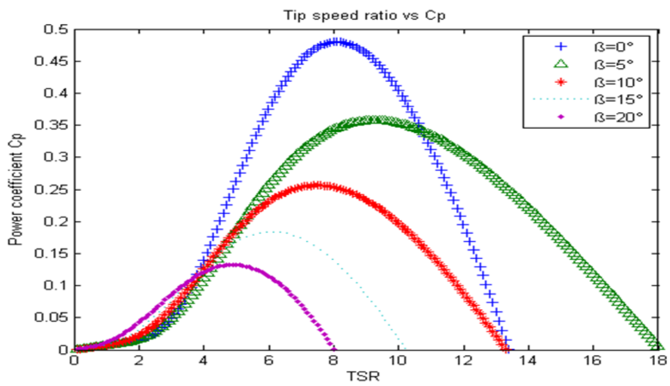

Fig. 5. The relation between $C_p(\lambda)$ and TSR (λ) at different pitch angle.

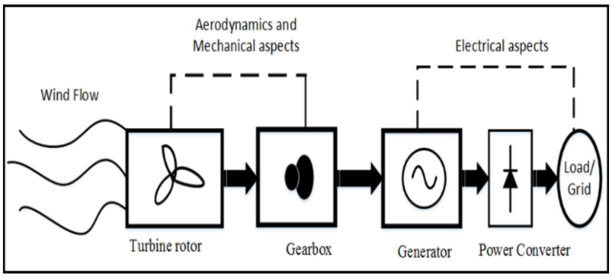

Fig. 6. A general layout of wind energy conversion system.

The connection between turbine and grid is done at different level of voltages. According to rotational speed of aero turbines WECS is basically categorized into two types, fixed speed and variable speed. Fixed speed system operates at almost constant speed. It concludes that irrespective of the speed of wind turbine, the rotor maintains a fixed angular speed, which is determined by supply frequency at grid and gear ratio. The drawback of such system is that any fluctuation in wind power has a direct impact on grid. In variable speed system the generator torque is kept fixed and generator speed is varied [23]. The generator speed can be adjusted to maximize the power extraction from the wind using rotor side power converter. A general layout of wind energy conversion system is shown in Fig. 6.

3.1. Generator system

Although several types of generators are employed in wind electricity market, but the permanent magnet synchronous generator(PMSG) and double fed induction generator(DFIG) are getting more and more attention day by day, due to their ability of being more reliable, and capturing more wind energy [24],[25]. Between the ac and dc generators, ac generator are more popular and mostly dominate the market due to lower expenditure, less maintenance, and higher rating. A classification of the different types of generators employed in WECS is given in the Fig. 7.

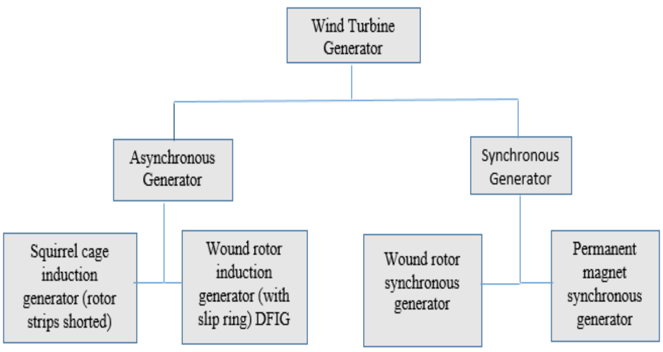

Fig. 7. Various commonly used wind turbine generator.

3.1.1. Synchronous Generator

Wind turbine using synchronous generator are often termed as gearless or direct drive wind turbine generator system. Nowadays, PMSG supported with different power electronics converter topology is getting huge attention to generate power from gearless wind turbine [26], [27]. Magnetic field in PMSG is produced by permanent magnet. It has received much focus due to its self-excitation capacity [28]. PMSG can be run with or without the gear. The power of gearless PMSG wind turbine system can be enhanced with using multiple number of poles. This arrangement can be directly connected to the grid without the gearbox, hence minimizing the mechanical loss, reducing the construction, maintenance and operation costs of the wind turbine generator system[29],[30]. The relatively lower weight of PMSG and its gearless wind turbine system design makes an attractive choice for its selection for variable speed wind power generator system. Due to their small size and weight PMSGs are particularly useful in low-power wind energy applications [31]. Thus the huge advantage of synchronous generator over induction generator in WECS is the absence of gearbox resulting an increase of system efficiency and reliability. Though absence of gearbox can be cost effective, it requires more number of poles to match the speed of gearless wind turbine with that of wind turbine with gear, making the direct drive generator larger and heavier. Therefore, indirect drive synchronous generator with lesser number of poles is still an acceptable choice in wind energy market [25].

3.1.2. Asynchronous generator

Due to simple operation, brushless structure, good dynamic response, and less price Induction generator (IG) are also vastly used as wind turbine generator [32]. They have robust structure and provide protection against short circuit. For its operation, IG needs reactive power to be fed to generate the magnetic field. A grid tied IG draw reactive power from grid. However, in standalone application, this reactive power can be supplied by external sources such as, power electronics converter, or bank of capacitors, called SEIG (self-excited induction generator) [33]. Owing to high cost of capacitors and maintenance requirement, SEIG is economically appropriate for small power plant [34], [35]. On the basis of rotor two type of induction generator is used as wind turbine generator, wound rotor induction generator (WRIG) and squirrel cage induction generator (SCIG). WRIG can be configured as DFIG which is widely used wind turbine generator nowadays. Variable speed operation using DFIG can be achieved by connecting the rotor circuit of DFIG by an external variable voltage through slip rings and controlled by external means [33]. The stator of DFIG is coupled with grid via transformer whereas rotor is connected through the grid via harmonic filter, power converter and the transformer. Connection of the stator with grid has a disadvantage that DFIG based WECS is more likely to be subjected to grid fault. The stator flux cannot follow abrupt change in stator voltage. The DFIG has one significant advantage that it can operate in the range of $\pm$ 30% of synchronous speed enough for normal speed variation. Hence, power converters for rotor is rated at 30% of stator power, significantly reducing cost and rating of power converter and harmonic filter. It also enables both sides of control i.e. grid side reactive power control and generator side active power control and [36]. Due to these some unique feature DFIG currently occupy nearly 50% of global wind electricity market [37].

3.1.3. Future Scope for Wind Generator System

There is serious concern about the impact of erratic wind power on the power system stability especially during grid fault. Therefore, one of the most attentional subject for researcher community is to develop ability for wind power generator system to protect itself during grid fault without being disconnected. Therefore, in the future, to design the generator with low weight & maintenance having fault ride through capability will be one of the main motive. Moreover, reduction in prices of generator system will be also great issue in the future. Therefore, not only being dependent upon commonly used wind turbine generators i.e. PMSG, DFIG or SCIG, focus should be given on the invention of other new types of generators. With light weight and about near zero resistivity superconductor based power devices has been area of intensive research nowadays. Size and weight are greatly reduced in high temperature superconductor (HTS) direct drive generator [38]. Superconductors have high current carrying capability. Moreover it shows characteristics of permanent magnet, hence it may be the preferred choice for PMSG. The stator and rotor of synchronous generator made out of HTS have huge advantages [39]. However stator is subjected to ac loss, therefore it is not practical to use stator made up of superconducting material. Hence there is need of careful design of the stator. Keeping in view to this a lot of research is going and various methods has been adopted [40].Nowadays, switched reluctance generator(SRG), made up of only magnetic core and winding having simple and robust structure is being utilized for high speed application[41]. Addition to this, it has high degree of freedom for shape and low moment of inertia making it favourable also for small scale WTs. However, SRG has drawback of having somewhat complicated circuitry because it needs both excitation circuit and a position sensor. Hence the current focus is on Permanent magnet reluctance generator (PMRG) especially designed for small scale WTs. Its stator yoke has permanent magnet that eliminates the need of both excitation circuit and position sensor making it simpler and more efficient than SRG [42], [43]. In future, possibility for the use of PMRG for large scale wind turbine generator system could be investigated. The careful exploration of existing wind generator system should lead to the development of advanced wind generator system in future and met the future need of wind power industry.

3.2. Development of Power Electronics

The nature of wind flow is very erratic in nature. It has varying daily and seasonal pattern. Therefore, it is not easy to operate a power system installed only with wind power generation unit. The power electronics helps the WECS to enhance its reliability and improve performance of the system by decreasing the mechanical stress and raising energy yield, because of which the whole WECS acts like controllable generation unit and enabling itself for better integration of wind power to grid [44]. Variable speed operation is more advantageous than fixed speed system for numbers of reasons, like reduced mechanical stress, greater power capture, better controllability and power quality, which are extremely needed for grid integration [45]. Thus variable speed wind turbines (WTs) has got better market penetration than fixed speed. The power electronics plays an important role in variable speed WTs (Fig. 8) [83]. It is evident that even in the fixed speed WTs, where power generator is directly linked with grid, thyristors-(power electronic semiconductor device), are used as soft starter. Though use of such power electronics converter may increase the cost of the system, this expense may be tolerated as it helps to reduce mechanical complexity, absorb mechanical stress minimizing the effect of wind gust. In many cases it eliminate the need of gearbox (Fig. 8(d)) which is main reason for losses and failure in wind turbine system. For wind electrical system many converter technologies are being employed [46]. Nowadays, in wind energy industry two level voltage source converter (VSCs) for DFIG [47] and PMSG [48] are mostly used. Many power converter of low power rating are being connected in series or parallel to handle high power originated from wind turbine generator making the system complex and incurring high manufacturing cost. Recently, for high power application, a back to back (BTB) pulse width modulation (PWM) current source converter (CSC) technique has been adopted. It gives better and magnificent performance for grid integration [49]. However, BTB current source converter suffers from problem of overvoltage that is frequently experienced by switches during commutation. To overcome this drawback a new back to back current source inverter (CSI) topology has been presented, in which switches are protected from overvoltage during commutation as in case of commonly used CSI [50].

3.2.1. Scope for Future Development

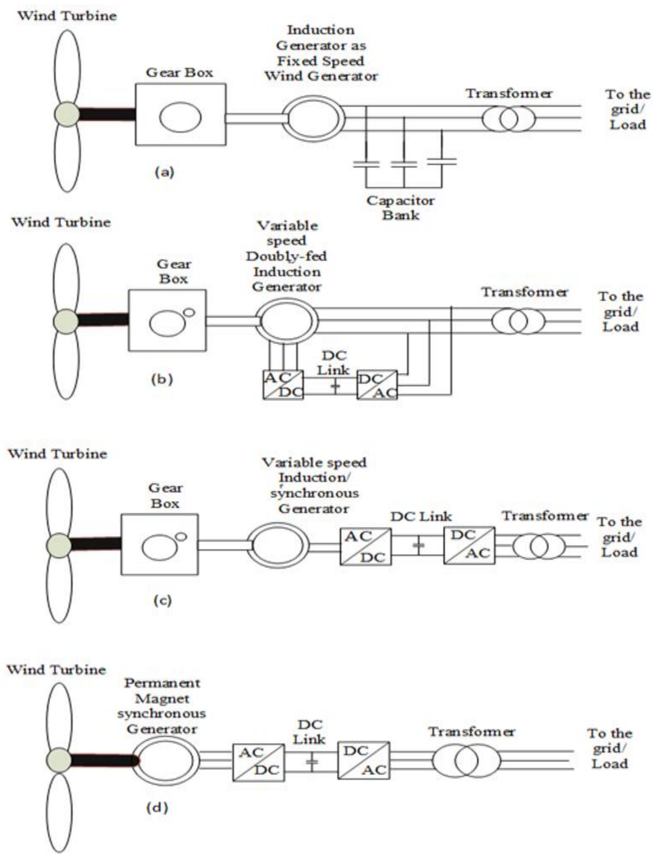

Fig. 8. Power electronics converters in WECS

To fulfil the fast growing demand and overcome the challenges present in wind energy conversion system some more advanced power electronic technologies can be expected to flourish in coming days where significant improvement could take place in power electronics converter to achieve power conversion at higher voltage level. A full scale power converter based back to back cascaded H-bridge converter, having galvanic insulated dc/dc converters as interface[51], may be one of the promising solution for future WECS. The dc-dc converter has medium frequency transformer operating at several kilohertz, reducing the transformer size significantly. The power semiconductor devices are linchpin in power converter design for wind electrical system. Nowadays, the potential silicon based power semiconductor devices used are pack-aged IGBT, press-pack packaged IGBT and the press packaging integrated gate commutated thyristor (IGCT) [52]-[54]. Recently, silicon carbide based devices which are primarily in the form of MOSFET as well as diode has gone through major development. From the above discussion it can be concluded that in the future, main aim of power electronics will be towards grid integration, enabling compatibility of wind power in the power system, lower cost and higher reliability.

3.3. Energy Storage Technology

Erratic wind power can cause severe problem in operation, stability and planning of power system. Therefore, for reliable power generation from wind energy, there is requirement of energy storage system (ESS) .The ESS stores the excess electrical energy produced and supply to load when there is shortage of power. Electric energy can be stored in different types of energy storage system as [56].

- kinetic energy in flywheel [57],
- compressed air,
- electric field in capacitors[58],
- superconductive magnetic energy storage[59],
- chemical energy in fuel cells,
- electrochemical energy in batteries [60],
- water reservoirs having gravitational potential energy.

Various types of ESS technology have been used for effective utilization of wind-electrical energy. To achieve overall better performance combined energy storage has also been used. A hybrid energy storage system composed of a superconducting magnet and secondary battery for an energy storage system has benefit of high energy density and high power density without rotating parts [61]. A supervisory control may also be adopted which will not only reduce power output variation but can also be helpful for control of frequency and damping of power swing [62]. In [63], sizing and control strategies for zinc –bromine flow battery based system has been presented. It shows that power flow control strategy have substantial impact on proper sizing of the rated power and energy of the system. A control scheme is developed for optimal use of BESS to smooth the intermittent power from wind farm [64].After going through several technical issues and different aspects related to their integration with power system, and management, various application of wind energy storage system are found out [65]. With such potential application it can be easily deduced that power quality, reliability and stability of WECS are remarkably improved with the integration of ESS in the wind power system. Some of the technical application of ESS in wind electrical system are as follows.

- Power fluctuation suppression
- Low voltage ride through(LVRT)
- Voltage control support
- Peak shaving
- Transmission Curtailment
- Load following
- Damping of oscillation

3.3.1. Future scope for energy storage system

Nowadays, huge effort is being given for improving the efficiency, capability as well as reducing the cost of ESS. The aim of research should be directed to make ESS economically feasible so as to make highest possible utilization of wind energy. To attain the future goal of higher wind electricity penetration into the market wakeful selection of storage technologies on the basis of desired operating condition, application, storage capacity and power rating is most sought after aspects for wind electricity generation. Life time and cost-effectiveness of present storage system need to be improved as much possible. The optimal size and their overall management together with the power system for obtaining the maximum economical advantage is going to be challenging task in future. Effective numerical optimization problem should be proposed in order to maximize the economical benefit from the storage device. Super capacitors with long lifetime of around 10^6 cycles, high power density, less maintenance cost, and being energy efficient (almost 80%), currently find use in renewable power system is one of the promising solution as a storage device [66]. Battery is extensively used as storage device in WECS. The design of controller, which will not only control the battery charging and discharging rate but also prevent battery from overcharging is a demanding feature of charge controller of battery bank. The main obstacle for full commercial effectuation of energy storage system in WECS is high cost of energy storage technology and uncertainty over desired benefit. Thus before installation of energy storage system, proper assessment on the economical feasibility of the storage technology should be done.

4. Control Issue in WECS

Research on WECS is mainly aimed to reduce the production cost, improving the quality of power and alleviate the overall system operation from the erratic nature of wind flow. To overcome these challenges researchers have come with various innovative control methodologies to address the various issue related to generated power, wind turbine speed and reliability. The control strategy is applied in various parts and subsystem of wind electrical system with different aims [91]. The control subsystem of WECS is mainly divided into three categories. A pictorial representation depicting different control techniques is shown in Fig. 9. Mainly three type of control are present, they are;

- Pitch control
- Maximum power point tracking(MPPT) control
- Machine /Grid side control

4.1. Pitch control

The pitch control strategy of wind turbines has an important role in controlling the wind power while ensuring the mechanical and electrical safety of the turbine at the same time. It prevent the wind turbine from fatigue damage during powerful wind gusts. Thus, WECS equipped with pitch control mechanism has significant influence on the wind power regulation and are of much importance for variable pitch wind turbines. During low wind speed the pitch angle of turbine is such adjusted that it increase the rotor speed. In the case of higher wind speed it acts as retarding force to lessen the rotor speed by increasing the pitch angle of turbine blade. In this way it protect the wind turbine system from damage. Pitch angle controller continuously monitors the angular velocity of wind turbine and adjust the pitch angle in order to control the speed of rotor and power [67]. Pitch control technique is divided generally in two types, electrical and hydraulic.

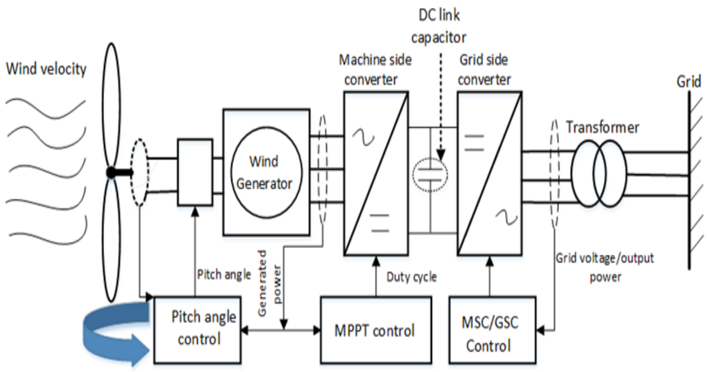

Fig. 9. A general layout of grid connected WECS showing different control subsystems [71].

4.1.1 Hydraulic Controller

Hydraulic pitch control is a drive system, which acts without an external power supply. Moreover, it is insensitive to vibrations and failure. Few non electrical component can ensure safe operation for WECS. Pitch control system is found in the hub of wind turbine. Hydraulic actuator with accumulator fluid tank is placed in the rotating hub which converts corresponding energy into the linear motion. A typical diagram of hydraulic pitch control is shown in Fig. 10. Several papers are available in literature with detailed information and novel idea to employ hydraulic pitch controller. Skare et al.[68], presented the complete mathematical model for hydraulic transmission system. Xiu-xing Yin et al. [69], presented a novel pitch control scheme for smoothing the output power and minimising drive-train torque fluctuation of the wind turbine. The system employing hydraulic pressure driven pitch control may suffer from inverse system dynamics and time delay making over control even more difficult. Anwar et al. [70] proposed a new PI controller design method using direct synthesis approach. Author adopts the method of frequency matching with the system to be designed to that of reference model of system.

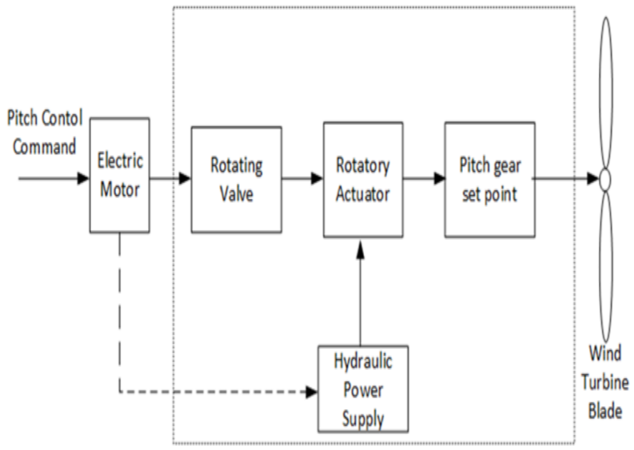

Fig. 10. Block diagram of hydraulic pitch control [71].

4.1.2 Electric Pitch control

Electric pitch controller comprises electro-mechanical actuator, electric motor, gearbox, power supply unit, and an energy storage unit. Actuator and gear box unit are placed in rotating hub whereas the power supply is placed in the nacelle. The purpose of energy storage unit is to provide power to pitch control system in case of main power failure. The electric pitch controller has faster response and more accuracy when compared to hydraulic controller but falls behind when robustness and safer operation is concerned. Many research papers are found in literature describing about different types of electrical pitch controller.

One of the electrical pitch controller is of conventional type, consist of PI/PID controller [72],[73], [74]. This type of controller is more suitable for small wind turbine system as it can't deal properly with the nonlinearity of the system. Therefore in order to cope with this, *Ren et. al*. [84] investigate nonlinear PI(N-PI) based pitch angel controller to bring down the power absorbed above the specified rated wind speed by designing a perturbation observer. The N-PI controller effective in terms of load stress reduction and dynamic performance

Large wind plants essentially influence the power system operation since they are heavily dependent on the nature of wind [75]. Therefore, to mitigate the erratic nature of wind soft computing based pitch control technique is employed. Soft computing has capability to solve wide range of problem. It is of predictive in nature and fast in response [76]. Many soft computing techniques such as Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), and Genetic Algorithm (GA) efficiently are used as means for pitch angle control. Several research works describing the functioning of soft computing for pitch control are reported in various literature. Fuzzy logic control (FLC) requires pre knowledge of control input variable and description of the system to design the rule base [77]. These rules ensures that operating range of the system lies within a limit. FLC has been used in solving numerous task in wind electrical system subjected to erratic flow of wind [78]. Tan Luong Van et al. [79], proposed a method for pitch angle control using FLC in variable speed wind turbine. Here generated output power and speed are taken as control input variable and reference pitch angle is produced by FLC. A smooth control is realized keeping output power and speed at rated value even in high speed wind. In the large WTs the effect of dynamic loading is important to be taken care of. Effect of these unbalanced structural load should be mitigated at any cost for proper regulation of power. This has prompted the development of individual pitch control (IPC). Bing Han et al. [80] designed a FLC for IPC to optimize a tradeoff between several control objectives and verified the method by simulation results for three-bladed 2 MW WT. Artificial neural network (ANN) is information processing system based on neural structure of the brain [81]. However, a typical ANN has a far simpler structure than biological neurons. It consists of input, hidden and output layer. Information flows between layers through their weights. A simple three layer neural multilevel perceptron is shown in Fig. 11. .Input to this network may be wind speed, generated torque/power, dc voltage/current whereas pitch angle, optimum torque/power and other constraints are kept on output side. The main benefit of ANN is that it does not need mathematical description of the system. A method of ANN application for pitch controller design is proposed in [82]. Several papers are available in the literature where collective methods comprising two or more techniques have been used. Proportional-integral-derivative (PID) controllers and genetic algorithms (GA) are vastly used for pitch angle control of turbine blade. However, tuning of PID controller and optimization of the GA controller is not easy in WT system. To overcome this problem Civelek et al. [86], suggested a new intelligent algorithm (IGA) algorithm approach for the PID controller tuning and optimization of the turbine blade. The algorithm combine both the crossover point number and mutation rate together as per the progress of the algorithm. Proposed scheme was found to be more efficient in adjusting the angle of the turbine blade particularly in the case of higher wind speed than other Genetic algorithm (GA) approach.

Most of the aforementioned pitch control techniques do not take account for unstructured dynamics of wind turbine, drive train, or the tower. Moreover, shifting of the operating point during operation and presence of nonlinearity in system dynamics pose challenges for turbine functioning. To address these challenges, some literature proposed robust pitch controller (RPC) that provides satisfactory functioning at different operating points under the given constraints [87-89].

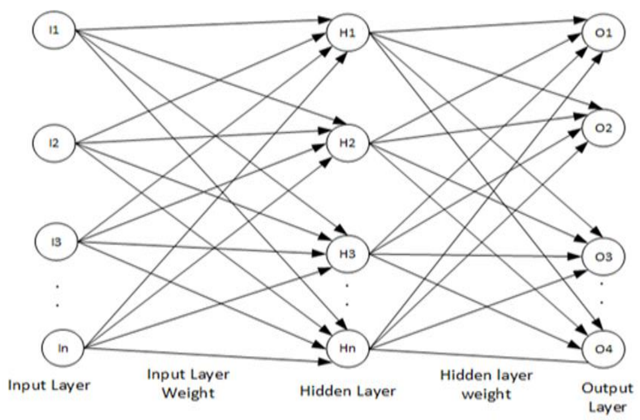

Fig. 11. A multilayer perceptron.

Hassan et. al. [90] designed a multi-objective collective RPC for large WT using state feedback Linear Matrix Inequalities techniques (LMI) for generator speed regulation. A polytopic model-based method is proposed to meet the desired constraints aimed for impeccable regulation, efficient disturbance rejection, and allowable actuator usage.

4.1.3. Hybrid Pitch Controller

To make pitch control technique more efficient and ensure safety of overall wind turbine system hybrid pitch control techniques are extensively used. This overcomes the drawback and lacunae of existing controller making it able for higher energy yield.

Kaisri et al. [92], proposed a new hybrid control technique. It contains a Multilayer Perceptron Neural Network (MLPNN) and Fuzzy whose rule base are extracted from trained artificial using genetic algorithm(FRENGA).This scheme generate required pitch angle by making comparison between MLPNN and FRENGA results. Author claim that proposed method is better than other techniques in regulating the output during wind variability.

Duong et al. [93] introduces a hybrid controller based on PI and fuzzy technique for the pitch angle controller for smoothing output power fluctuations. Author apply the controller for SCIG wind farm for improvement in power quality and output stability, minimizing the effect of inconsistency of the wind.

Lin et.al. [94] proposed a pitch control technique employing fuzzy sliding mode control and Radial basis function neural network(RBFN) to control the pitch angle and speed of wind turbine. The back-propagation algorithm is used to adjust the RBFN controller. This method helps in keeping the system stable and obtaining the desired performance under the parameter variations and erratic wind power.

4.1.4 Current Trends and Future Research Direction

Modern wind turbines (WTs) are generally large in size. Thus effect of dynamic loading on the whole structure becomes an important influence factor. It has inspired the researcher for development of individual pitch control (IPC) methodologies. Therefore, there are efforts to mitigate the unwanted dynamic effect of these unbalanced structural load and regulate power efficiently. Wind turbine is a complex electro-mechanical structure whose performance largely suffers with variation in speed of wind. Single control strategy for pitch angle is not sufficient in most of the cases. Currently, research is going on combining multiple existing control strategy suitably to design an integrated/hybrid control system. Such kind of work is summarized previously in this paper.

4.2. Maximum power point tracking (MPPT) control

One of the most desirable feature of WECS is its ability to extract maximum power under varying wind speed. It is essential for WTs to track fast the variation in wind velocity in pursuance of supplying maximum possible power to the load/grid. It is known (from equation no. (2)), the mechanical power seized by the turbine blade depends upon power coefficient (Cp), density, velocity of air, and radius of the turbine blade. Radius and density for a particular wind turbine at any location is fixed. Thus, the power contained in the turbine depends mainly upon Cp. It again can be seen (from equation (3)-(5)) that Cp depends upon angular velocity of wind turbine. So in order to capture maximum power at a given wind turbine should be rotated at an optimal angular velocity (Fig. 12). Thus MPPT control enables WECS to maximize its efficiency by extracting maximum possible energy from wide range of wind speed values. Therefore, it is important to integrate a MPPT control strategy into the WT in order to its operating point at the optimal value. Many MPPT theories have been developed so far with prime concern as how to effectively achieve highest possible yield from wind every time. Based on maximization of output power MPPT control is generally divided into two category (Fig. 13), indirect power

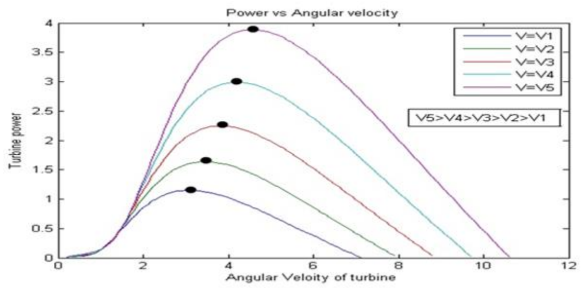

Fig. 12. Characteristics between turbine output power and angular velocity of wind turbine

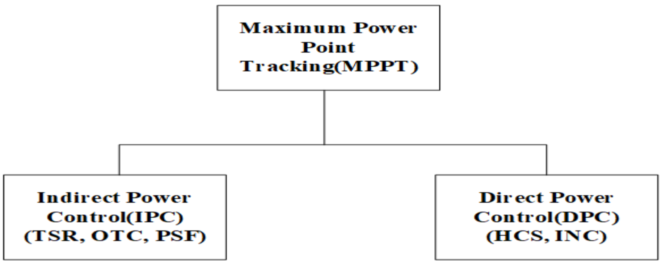

Fig. 13.Classification of MPPT on the basis of maximization of output power

control (IPC) and direct power control (DPC) [95]. IPC maximizes mechanical output power from wind turbine, whereas DPC maximizes the obtained output electrical power directly from the turbine generator.

Several MPPT control techniques based on both IPC and DPC have been proposed in the literature. The most popular and widely used MPPT techniques are Hill climbing search (Perturb & Observe), Incremental conductance (INC), Tip speed ratio (TSR), Power signal feedback (PSF). Optimal torque control (OTC).

The **Hill climb searching (HCS)** [22] is implemented by perturbing the control variable and detecting the subsequent upsurge or fall in power. For this reason it is also named as perturb and observe (P&O) control. If upsurge in power is detected, then the unchanged perturbation is utilized for the afterward control step, else in the event of fall in power, direction of the perturbation is inverted so that changing power could be tracked. This method does not require the sensors to measure wind or generator speed or any erstwhile knowledge of the WTs. Therefore, this control is still very favourable choice among other control techniques. However, the method suffer from serious problem. If the size of perturbation step is large (Fig. 14(a)) then speed of convergence is fast but efficiency is affected due to amplification of amplitude around MPP. On the contrary, small perturbation steps size (Fig. 14(b)) enhance the efficacy but diminish the MPPT control speed resulting in false MPPT point deduction. In addition, under the circumstances of rapid change in wind speed, the direction of next step perturbation which is determined by change in power due to prior perturbation may be highly ambiguous.

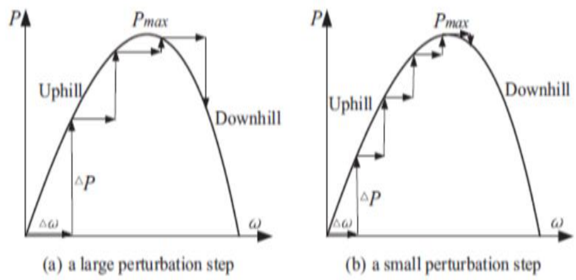

Fig. 14. Principle of hill climbing search control.

Basic principle of **Incremental conductance (INC) control** [96], underlie in the fact that tangent slope of power-voltage characteristics have to be zero at maximum power point(MPP). On the right side of MPP slope should be negative, and positive on the left side. The advantage of this MPPT technique is that it doesn't not need sensors or knowledge of machine specification.

In **Tip speed ratio** [97, 98, 101] method angular velocity of wind turbine is regulated, to keep the tip-speed ratio at optimum level and draw maximal available power from wind. Optimal angular velocity obtained from the relationship shown in equation (5) is put into comparison with the real value. The difference in the form of error is sent to controller which change the speed of the generator to minimise the difference. Though this method is simple in implementation, it incurs high cost due to anemometer and other complex circuitry used for precise measurement of wind speed.

Power Signal Feedback (PSF) [99] require the knowledge of power curve which can be obtained from experiment or simulation. It generates a reference power signal which is then applied to grid side converter for maximum power extraction. In this method, optimal power is produced with the help of previously found power–speed curve, or using the formula of power curve which is given by the equation, $p_{opt} = k_{opt} \times \omega_r^{\,3}$. The PSF control method adjusts the turbine power to stay it upon an optimal value, so that power coefficient *Cp* remain at its peak value corresponding to the optimal TSR.

Optimal Torque control (OTC) [100,101] regulates torque of the generator to its optimum value and find optimum torque reference characteristic as per the peak power of the WT at a certain wind speed. This method is used widely, though there are some drawbacks present in the method as it needs the measured data as density of air and other WT mechanical parameter.

In addition to all the previously mentioned MPPT methods there are some **soft computing** based techniques which are being vastly used nowadays. These techniques have the advantages that they do not require mathematical description of the system and parameter variation has no effect on such type of techniques. Fuzzy logic controller (FLC) [102-104] and Artificial neural network (ANN) [105-107] have found substantial space as MPPT controller in various literature. The fuzzy-logic-based MPPT control techniques are advantageous due to fast convergence, parameter insensitivity and its ability to cope the non-linearity of wind electrical system very well. The effectiveness of FLC rely upon the knowledge of user about system to decide appropriate error, selection of rule base and membership function. With the increase in use of soft computing techniques as MPPT controller ANN has seen remarkable growth till now. ANN typically consist of three layers, input, hidden and output as shown in Fig. 12. In WECS, it take combination of DC voltage/current, wind velocity and rotor speed as input whereas reference signal such as reference torque, rotor speed and reference generator power are generally taken as output for ANN.

4.2.1 Recent trend and Future Scope

The above mentioned MPPT algorithm if used alone efficient may not be efficient enough in many cases. In PSF control, earlier information of turbine's maximum power curve found through either offline experimentation or computer simulations is required. In HCS (P&O) control technique, a random slight perturbation is applied to one of the free variables of the system and next perturbation is determined depending on the deviations in output power due to previous perturbation. Thus under fast changing wind speed it may be very confusing to decide the next direction for perturbation. Moreover, disadvantages of these techniques are, sluggish tracking response, particularly for the systems which possesses high inertia. Thus current trends towards MPPT techniques are **Hybrid controller** which comprises of two or more methods are generally be used to fill the lacunae of any existing MPPT method. Hussain et. al. [108], proposed a hybrid MPPT control which combines the property of TSR-PSF-HCS algorithms for adaptability and fast tracking ability of MPP under wide range of wind velocity profile. It was found that system performance with the algorithm extract greater energy than with P&O algorithm. Many sensor less techniques are being employed nowadays to track maximum power from wind making the system more robust. [109]. Daili et. al. [110], proposed algorithm that does not require mechanical sensors or information of system parameter. The future research direction for the MPPT technology may be to design and implement the method which is less dependent on the machine and wind turbine parameters. A brief survey of some recent MPPT algorithm is given in the Table 1.

4.3. Grid/Machine side control

The function of grid side controller (GSC) is to control the reactive and active power flow to the grid by regulating the dc link voltage. Control of the Machine side controller (MSC) permits the generator to regulate the rotating speed as per the wind speed change to achieve maximum power [118]. MSC is classified into field oriented control (FOC) and direct torque control (DTC) (Fig. 15). These two control techniques are employed for generators in WECS. In the FOC control scheme, wind generator three phase current is

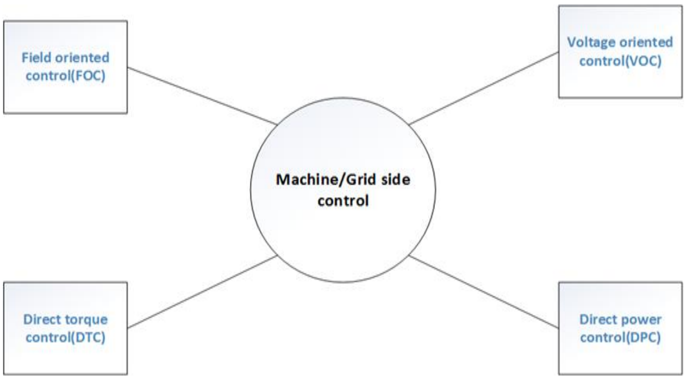

Figure. 15. Grid and Machine side control.

transformed into two orthogonal components [120] that define electromagnetic torque and magnetic flux, A reference voltage vector is generated in the modulation stage with the help of two PI controller to make the measured current to track thereference current. The FOC require knowledge of the shaft speed, which is determined by an encoder as a feedback [119]. Apart from this speed loop, it permits separate and indirect control of the toque and flux by means of the current control loop. Such type of control have many benefits such as decent torque response and precise speed control.

DTC is considered as potential alternative to FOC control scheme. In place of generator current control, it directly control stator flux and electromagnetic torque with the help of look up table and hysteresis control. It is relatively simple to implement compared to FOC as it does not need coordinate transformation, PI controller and PWM modulation [120]. DTC is based mainly upon space vector theory. It obtain effective control of torque and stator flux by optimal selection of space voltage vector [121].

Grid side control (GSC) mainly emphasis on the problem arising due to integration of wind power into grid. It is primarily employed to control power sent to the grid, to retain the DC-link voltage fixed, and to safeguard the quality of the power injected to the grid. These control objectives can be achieved by using direct power control (DPC) or voltage oriented control (VOC) [122]. A VOC is similar to FOC which include dual loop control structure. Such a control scheme is shown in [123], where d-axis is associated with stator-voltage space vector and utilized to control the torque whereas q-axis control the reactive power. DPC control helps in keeping the DC link voltage to reference value and adjusting the reactive power in the system. It can be seen [124] that control techniques adopted without taking consideration of system unbalance causes disproportionate oscillations in the stator active/reactive power and electromagnetic torque. To overcome the

S.N	Ref	Year	Algorithm/ Technique	Types of Machines	Hardwar/Software Tools	Publisher
1	111	2015	Genetic	SEIG	MATLAB & dsPIC30F4011	IEEE
2	112	2016	Neural	PMSG	PSCAD/EMTDC & dSPACE1104	IEEE
3	113	2015	LMA	IPMSG	MATLAB & DS1104	IEEE
4	114	2016	FLC, P&O	SCIG	PSIM & DSP	IET
5	115	2016	PSF	BDFRG	MATLAB/Simulink	IJRER
6	116	2014	Fuzzy-SMC, Grey wolf	IG	MATLAB/Simulink	IJRER
7	117	2015	Backstepping algorithm	PMSG	MATLAB/Simulink	John Wiley & Sons, Inc.

the mechanical problem caused by fluctuation in torque, a DPC control technique based upon appropriate active and reactive generation reference generation strategy is proposed [125]. Some more DPC strategies were later developed to cope with unbalanced grid voltage conditions. A predictive current control approach was developed with having advantage of rapid dynamic response [126]. This type of scheme was based on the prediction and somewhat complex to implement. A relative simpler control strategy based upon sliding mode control (SMC) technique [127] are robust against variation of parameter and under dissimilar grid voltage conditions. However, there is no any discussion on improvement on power quality. To get over mentioned issue and increase control flexibility, Hu et al. [128] proposed a new technique called model predictive direct power control (MPDPC).The work under unbalanced grid voltage condition offer power compensation for numerous control strategy under unbalanced grid voltage condition. Moreover, it eradicate the need of coordinate transformation, switching tables, PI controller, and pulse-width modulators and therefore achieving good dynamic response.

4.3.1. Future research scope

Grid connected WECS is usually very large in size and capacity. Integration of grid with wind power system inflict numerous challenges such as power quality, frequency and voltage control, harmonics, flickers and stability that must be carefully addressed. Many control issue in grid connected or standalone wind power system exist which require careful consideration by researcher in future. Some of the important among them are and nonlinear plant dynamics, presence of unpredictable disturbance associated with dynamic loading. The machine side voltage source converter (VSC) control the dc-link voltage via changes in the generator speed [129]. Existence of parametric uncertainness accompanying with the corresponding dc-link capacitance due to connection and detachment of converter-based loads diminish the controller performance. Thus there is need to design a robust dc link controller that will supress this problem. WECS should have the capability of maintaining synchronism in the situation of severe disturbances. Generator need to have the low/high voltage fault ride through (FRT) capability, i.e generator ought to be stay coupled with the grid in case of voltage mismatch with rated voltage in case of any unexpected situation arises. Therefore, the research should be focussed on finding device to improve FRT capability.

5. Guideline for the Certification of Wind Turbines

The rapid development of the wind energy industry and increasing size of wind farms and turbine demand more reliability and safety measure of projects related to wind power. The measures are carried out as per certification of various components of WTs. Within the context of the certification of wind turbines, reliability, safety, strength and fatigue are estimated in order to ensure safe operation[130]. Germanischer Lloyd Industrial Services GmbH, Renewables Certification (GL) is a worldwide operating certification body for wind turbines, wind farms and related technologies. Moreover, GL is sanctioned to carry out certification as per all relevant national and international standards in the field of wind energy[131].

The International Electro technical Commission (IEC) is a worldwide organization for standardization comprising all national electro technical committees (IEC National Committees). The object of IEC is to promote worldwide co-operation on all questions concerning standardization in the electrical and electronic area. In addition to these activities, IEC publishes international standards, technical specifications and technical reports.

IEC 61400 is an International Standard published by IEC regarding wind turbine. It is a set of design requirements divided in several parts to ensure that wind turbines are appropriately designed to withstand against damage from hazards within the planned lifetime. Some important parts of IEC 61400 with their main objectives are summarised below [132].

- **IEC 61400-1**: Design requirement for wind turbine, concerned with all subsystems of wind turbines such as control and protection mechanism, mechanical system and support structure.

- **IEC 61400-2**: Particularly deals with safety, quality, and engineering integrity of small wind turbine.

- **IEC 61400-3**: Specifies additional assessment of the external condition and essential design requirement for an off shore wind turbine system.

- **IEC 61400-4**: Provides guidance to design the gear boxes.

- **IEC 61400-11**: Provide noise measurement techniques, with the aim to minimize the effect of sound from wind turbine.

- **IEC 61400-12-1**: Power performance measurements of electricity produced.

- **IEC 61400-12-2**: Specifies a procedure for verifying the power performance characteristics of a single electricity-producing, horizontal axis wind turbine, which is not considered to be a small wind turbine as per part IEC 61400-2.

- **IEC 61400-13**: Measurement of fundamental mechanical loads on wind turbine for the purpose of load simulation model validation.

- **IEC 61400-14**: Gives guidelines for stating the apparent sound level.

- **IEC 61400-21**: Provide definition and specification of the quantities to be determined for characterizing the power quality of a grid connected wind turbine. The publication is of high relevance to smart grid.

- **IEC 61400-22**: Specifies rules for procedures and management for carrying out conformity evaluation of WT and wind farms, with respect to specific standards and other technical requirements, relating to safety, reliability, performance, testing and interaction with electrical power networks.

- **IEC 61400-24**: Defines measures for protection of blades, other structural components, electrical and control systems against both direct and indirect effects of lightning.

- **IEC 61400-25**: This part (series) deals with communications between wind power plant and system such as SCADA. It is aimed to launch communication environment backed by a client-server model.

6. Conclusion

This work is mainly study on different technical aspects for harnessing wind energy. Current trends and future possible research directions associated with energy conversion technology is presented. Need of the present hour is to exploit the available wind energy at every corner of earth to meet our energy demand.

The variable speed DFIG based WECS is most popular. But, with the growing need of the system reliability and generator with fault ride through capability, the direct-drive system with full-scale converter and PMSG is also getting more attention as wind turbine generator. For reliable operation of WECS there is need of an efficient energy storage system (ESS) and hence developing a simple and the economical procedure for the same. Before setting up ESS, proper assessment on the commercial feasibility of the storage technology should be done. Intermittent nature of wind poses difficult task before the control techniques in WECS to obtain reliable and consistent power supply. Importance of power electronics in the wind electrical system has been demonstrated. Power electronics converters increase reliability and improve performance of the system by decreasing the mechanical stress and enhancing energy yield. There is need of more and more investigation in power electronics side for reliable and simplified grid integration. A review of technologies related to different control strategy found for MPPT, pitch control and GSC/MSC is presented. IEC standard and GL guidelines for the proper design, safety and operation are mentioned in brief.

Last but not the least, this study inquire into different control strategy and outlines several past research work related to wind energy conversion along with current research trends and future scope. This article would help researchers to find valuable information regarding wind power system.

Acknowledgements

We would like to thank the Editor and Reviewers for their valuable comments. The support of National Institute of technology Jamshedpur for the work is acknowledged.

References

[1] A. D. Sahin, "Progress and recent trends in wind energy," *Progress in Energy Combustion Sci.*, vol. 30, no. 5, pp. 501–543, 2004.

[2] Manfred Stiebler, *Wind Energy Systems for Electric Power Generation*, Springer-Verlag Berlin Heidelberg, 2008.

[3] Kaoshan Dai, Anthony Bergot, Chao Liang, Wei-Ning Xiang, Zhenhua Huang, "Environmental issues associated with wind energy – A review*," Renewable Energy*, vol. 75, pp. 911-921, March 2015.

[4] R. Saidur, M. R. Islam, N. A. Rahim, and K. H. Solangi, "A review on global wind energy policy," *Renewable Sustainable Energy Rev.*, vol. 14, no. 7, pp. 1744–1762, Sept. 2010.

[5] US Department of energy, International energy outlook 2013.Technical report DOE/EIA-0484.US Department of energy, 2013, http://www.eia.gov/forecasts/ieo/pdf/0484 (2013).pdf

[6] National Research Council. Advancing the science of climate change. Washington, DC, USA: The National Academies Press; 2010.

[7] Devashish, A. Thakur, S. Panigrahi and R. R. Behera, "A review on wind energy conversion system and enabling technology," *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, Bhopal, pp. 527-532, Dec. 2016.

[8] Global wind energy council, "Global wind report-2016-Annual market update."

[9] Global wind energy council, India Wind Energy Outlook, 2012.

[10] M. Yesilbudak, S. Sagiroglu and I. Colak, "A wind speed forecasting approach based on 2-dimensional input space," *2012 International Conference on Renewable Energy Research and Applications (ICRERA)*, Nagasaki, pp. 1-5, 2012.

[11] Yogesh Kumar, Jordan Ringenberg, Soma Shekara Depuru, Vijay K. Devabhaktuni, Jin Woo Lee, Efstratios Nikolaidis, Brett Andersen, Abdollah Afjeh, "Wind energy: Trends and enabling technologies*," Renewable and Sustainable Energy Reviews*, vol. 53, Jan. 2016, pp. 209-224.

[12] John K. Kaldellis, D. Zafirakis, "The wind energy evolution: A short review of a long history, *Renewable Energy*," vol. 36, Issue 7, pp. 1887-1901, July 2011.

[13] "The inside of a wind turbine," U.S. Department of energy, Office of Energy Efficiency & *Renewable Energy*, Washington D.C.

[14] L. H. Hansen, P. H. Madsen, F. Blaabjerg, H. C. Christensen, U. Lindhard and K. Eskildsen, "Generators and power electronics technology for wind turbines," *Industrial Electronics Society, 2001. IECON '01. The 27th Annual Conference of the IEEE,* Denver, CO, 2001, pp. 2000-2005, 29 Nov-2 Dec. 2001.

[15] J. Lloberas, "Finite-Element Analysis of a 15-MW High-Temperature Superconductor Synchronous Generator for Offshore Wind Energy Applications," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 6, pp. 1-7, Dec. 2015.

[16] G. Snitchler, B. Gamble, C. King and P. Winn, "10 MW Class Superconductor Wind Turbine Generators," *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, pp. 1089-1092, June 2011.

[17] K. Suffer, R. Usubamatov, G. Quadir and K. Ismail, "Modeling and Numerical Simulation of a Vertical Axis Wind Turbine Having Cavity Vanes," *2014 5th International Conference on Intelligent Systems, Modelling and Simulation*, Langkawi, pp. 479-484, 27-29 Jan. 2014.

[18] P. D. A. Aziz, A. K. R. Mohamad, F. Z. Hamidon, N. Mohamad, N. Salleh and N. M. Yunus, "A simulation study on airfoils using VAWT design for low wind speed application," *2014 4th International Conference on Engineering Technology and Technopreneuship (ICE2T)*, Kuala Lumpur, pp. 105-109, 27-29 Aug 2014.

[19] Cheng, Z., Wang, K., Gao, Z., and Moan, T, "A comparative study on dynamic responses of spar-type floating horizontal and vertical axis wind turbines," *wind energy*, vol. 20, no. 2, pp. 305-323 July 2016.

[20] Wei Qiao and Dingguo Lu, "A Survey on Wind Turbine Condition Monitoring and Fault Diagnosis−Part I: Components and Subsystems," *IEEE Trans Ind. Electron*. vol. 62, no. 10, pp. 6536 – 6545, April 2015.

[21] S.M Muyeen, "Wind *energy conversion system-Technology and Trends*," Springer –verlag London limited 2012.

[22] Zakariya M. Dalala,, ZakaUllah Zahid, Wensong Yu, Younghoon Cho and Jih-Sheng (Jason) Lai, "Design and Analysis of an MPPT Technique for Small-Scale Wind Energy Conversion Systems," *IEEE Transactions On Energy Conversion*, vol. 28, no. 3, pp. 756-767, Sept. 2013.

[23] Rajeev Mittal, K.s. sandhu and D.K Jain , "An overview of some important issue related to wind energy conversion system," *International Journal of Environmental science and development*, vol.1, no.4, pp. 351-363, Oct 2010.

[24] Hua Geng and Dewei(David) Xu, "Stability Analysis and Improvements for Variable-Speed Multipole Permanent Magnet Synchronous Generator-Based Wind Energy Conversion System, "*IEEE Trans. On Sustainable Energy*, vol. 2, no. 4, pp. 459-467, Oct. 2011.

[25] H. Polinder, F. van der Pijl, G.-J. de Vilder, and P. Tavner, "Comparison of direct-drive and geared generator concepts for wind turbines*," IEEE Trans. Energy Convers*., vol. 21, no. 3, pp. 725–733, Sep. 2006.

[26] A. Harrouz, I. Colak and K. Kayisli, "Control of a small wind turbine system application," *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, Birmingham, pp. 1128-1133, 2016.

[27] F. Blaabjerg, M. Liserre, &K. Ma, " Power Electronics Converters for Wind Turbine Systems, " *IEEE Trans. Ind. Appl*., vol. 48, no. 2, pp. 708-719, Mar. 2012.

[28] C. N. Bhende; S. Mishra; S. G. Malla, " Permanent magnet based standalone wind energy power supply," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 4, pp. 361-373, Oct. 2011.

[29] W. Qiao, X. Yang and X. Gong, "Wind Speed and Rotor Position Sensorless Control for Direct-Drive PMG Wind Turbines," *IEEE Transactions on Industry Applications*, vol. 48, no. 1, pp. 3-11, Jan.-Feb. 2012.

[30] W. Qiao, L. Qu and R. G. Harley, "Control of IPM Synchronous Generator for Maximum Wind Power Generation Considering Magnetic Saturation," in *IEEE Transactions on Industry Applications*, vol. 45, no. 3, pp. 1095-1105, May-june 2009.

[31] L. Barote, C. Marinescu, M. N. Cirstea, "Control Structure for Single-Phase Stand-Alone Wind-Based Energy Sources, " *IEEE Trans. Ind. Electron*., vol. 60, no. 2, pp. 764-772, Feb.2013.

[32] C. S. C. do Nascimento and A. F. F. Filho, "Design of an induction generator with copper squirrel cage rotor and asymetric slots," *2014 International Conference on Renewable Energy Research and Application (ICRERA)*, Milwaukee, WI, pp. 544-549, 2014.

[33] Farret, F.A. and Simões, M.G., *Integration of Alternative Sources of Energy*, Wiley IEEE Press, 2006.

[34] S. S. Murthy, O. P. Malik and A. K. Tandon, "Analysis of self-excited induction generators," *IEE Proceedings C - Generation, Transmission and Distribution*, vol. 129, no. 6, pp. 260-265, November 1982.

[35] A. K. Tandon, S. S. Murthy and G. J. Berg, "Steady State Analysis of Capacitor Self-Excited Induction Generators," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 3, pp. 612-618, March 1984.

[36] Wu B, Lang Y, Zargari N, Kouro S, "*Power conversion and control of wind energy system*," 1st ed. New Jersy, USA: Wiley; 153-315.

[37] R. Cardenas, R. Pena, S. Alepuz and G. Asher, "Overview of Control Systems for the Operation of DFIGs in Wind Energy Applications," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 7, pp. 2776-2798, July 2013.

[38] G. Snitchler, B. Gamble, C. King and P. Winn,"10 MW Class Superconductor Wind Turbine Generators," *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, pp. 1089-1092, June 2011.

[39] M. E. Khalil, "High temperature superconducting generator design for offshore wind turbine application," *Electrical Engineering and Information Communication Technology* (ICEEICT), 2015 International Conference on, Dhaka, pp. 1-6, 2015.

[40] L. H. Zheng, X. Q. Li and J. X. Jin, "Technology research of high temperature superconducting wind

turbine generator," *2015 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices* (ASEMD), Shanghai, China, pp. 5-6, Nov. 20-23.

[41] R. Cardenas-Dobson, W. F. Ray and G. M. Asher, "Switched reluctance generators for wind energy applications", *Proc. 26thAnnu.IEEE Power Electron. Specialists Conf.*, vol. 1, pp. 229-564, 1995.

[42] K. Nakamura , J. Yoshida and O. Ichinokura, "Stator-permanent-magnet reluctance generator using ferrite magnet for small-scale renewable energy generation", EPE J., vol. 20, no. 4, pp. 31-36, 2010.

[43] K. Nakamura and O. Ichinokura, "Super-Multipolar Permanent Magnet Reluctance Generator Designed for Small-Scale Wind-Turbine Generation,"*IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 3311-3314, Nov. 2012.

[44] F. Blaabjerg and K. Ma, "Future on Power Electronics for Wind Turbine Systems," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 139-152, Sept. 2013.

[45] A. Venkataraman, A. I. Maswood, S. N. Rahman and O. H. P. Gabriel, "A novel maximum power point tracking algorithm for a stand-alone unity power factor wind energy conversion system," *2013 International Conference on Renewable Energy Research and Applications (ICRERA)*, Madrid, pp. 109-114, 2013.

[46] T. Nakanishi, K. Orikawa and J. i. Itoh, "Modular Multilevel Converter for wind power generation system connected to micro-grid," *2014 International Conference on Renewable Energy Research and Application (ICRERA)*, Milwaukee, WI, pp. 653-658, 2014.

[47] J. Yao, H. Li, Y. Liao and Z. Chen, "An Improved Control Strategy of Limiting the DC-Link Voltage Fluctuation for a Doubly Fed Induction Wind Generator," *IEEE Transactions on Power Electronics*, vol. 23, no. 3, pp. 1205-1213, May 2008.

[48] S. Grabic, N. Celanovic and V. A. Katic, "Permanent Magnet Synchronous Generator Cascade for Wind Turbine Application," *IEEE Transactions on Power Electronics*, vol. 23, no. 3, pp. 1136-1142, May 2008.

[49] J. Dai, D. Xu and B. Wu, "A Novel Control Scheme for Current-Source-Converter-Based PMSG Wind Energy Conversion Systems," *IEEE Transactions on Power Electronics*, vol. 24, no. 4, pp. 963-972, April 2009.

[50] I. Abdelsalam, G. P. Adam, D. Holliday and B. W. Williams, "Modified back-to-back current source converter and its application to wind energy conversion systems," *IET Power Electronics*, vol. 8, no. 1, pp. 103-111, 2015.

[51] F. Iov, F. Blaabjerg, J. Clare, O. Wheeler, A. Rufer, and A. Hyde, “UNIFLEX-PM—A key-enabling technology for future European electricity networks,” *EPE J.*, vol. 19, no. 4, pp. 6–16, 2009.

[52] K. Ma and F. Blaabjerg, “The impact of power switching devices on the thermal performance of a 10 MW wind power NPC converter,” *Energies*, vol. 5, no. 7, pp. 2559–2577, 2012.

[53] R. Jakob, C. Keller, and B. Gollentz, “3-level high power converter with press pack IGBT,” in Proc. EPE, Sep. 2007, pp. 2–5.

[54] R. Alvarez, F. Filsecker, and S. Bernet, “Comparison of press-pack IGBT at hard switching and clamp operation for medium voltage converters,” *Proc. EPE*, 2011, pp. 1–10.

[55] S. Teleke, M. E. Baran, A. Q. Huang, S. Bhattacharya and L. Anderson, "Control Strategies for Battery Energy Storage for Wind Farm Dispatching," *IEEE Transactions on Energy Conversion*, vol. 24, no. 3, pp. 725-732, Sept. 2009.

[56] Francisco Díaz-González, Andreas Sumper, Oriol Gomis-Bellmunt, Roberto Villafáfila-Robles, “A review of energy storage technologies for wind power applications,” *Renewable and Sustainable Energy Reviews*, Volume 16, Issue 4, pp. 2154-2171, May 2012.

[57] M. Chudy, L. Herbst and J. Lalk, "Wind farms associated with flywheel energy storage plants,” *IEEE PES Innovative Smart Grid Technologies*, Europe, Istanbul, pp. 1-6, 2014.

[58] S. M. Muyeen, R. Takahashi, T. Murata and J. Tamura, "Integration of an Energy Capacitor System with a Variable-Speed Wind Generator," *IEEE Transactions on Energy Conversion*, vol. 24, no. 3, pp. 740-749, Sept. 2009.

[59] T. Nam, J. W. Shim and K. Hur, "The Beneficial Role of SMES Coil in DC Lines as an Energy Buffer for Integrating Large Scale Wind Power," *IEEE Transactions on Applied Superconductivity*, vol. 22, no. 3, pp. 5701404-5701404, June 2012.

[60] D. L. Yao, S. S. Choi, K. J. Tseng and T. T. Lie, "A Statistical Approach to the Design of a dispatchable Wind Power-Battery Energy Storage System," *IEEE Transactions on Energy Conversion*, vol. 24, no. 4, pp. 916-925, Dec. 2009.

[61] T. Ise, M. Kita and A. Taguchi, "A hybrid energy storage with a SMES and secondary battery," *IEEE*

Transactions on Applied Superconductivity, vol. 15, no. 2, pp. 1915-1918, June 2005.

[62] Z. Lubosny and J. W. Bialek, "Supervisory Control of a Wind Farm," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 985-994, Aug. 2007.

[63] T. K. A. Brekken, A. Yokochi, A. von Jouanne, Z. Z. Yen, H. M. Hapke and D. A. Halamay, "Optimal Energy Storage Sizing and Control for Wind Power Applications," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 1, pp. 69-77, Jan. 2011.

[64] S. Teleke, M. E. Baran, A. Q. Huang, S. Bhattacharya and L. Anderson, "Control Strategies for Battery Energy Storage for Wind Farm Dispatching," *IEEE Transactions on Energy Conversion*, vol. 24, no. 3, pp. 725-732, Sept. 2009.

[65] F. D. Gonz´alez, A. Sumper, O. G. Bellmunt, and R. V. Robles, “A review of energy storage technologies for wind power applications,” *Renewable and Sustainable Energy Rev*., vol. 16, no. 4, pp. 2154–2171, May 2012.

[66] A. M. Gee, F. V. P. Robinson and R. W. Dunn, "Analysis of Battery Lifetime Extension in a Small-Scale Wind-Energy System Using Supercapacitors," *IEEE Transactions on Energy Conversion*, vol. 28, no. 1, pp. 24-33, March 2013.

[67] T. L. Van, T. H. Nguyen and D. C. Lee, "Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems," *IEEE Transactions on Energy Conversion*, vol. 30, no. 2, pp. 578-587, June 2015.

[68] Bjørn Skaare, Bo Hörnsten and Finn Gunnar Nielsen, “Modeling, simulation and control of a wind turbine with a hydraulic transmission system,” Wind Energy, wiley online librarary, vol. 16, Issue 8 , pp. 1259–1276, November 2013.

[69] Xiu-xing Yin, Yong-gang Lin, Wei Li, Ya-jing Gu, Xiao-jun Wang, Peng-fei Lei, Design, modeling and implementation of a novel pitch angle control system for wind turbine, *Renewable Energy*, Volume 81, pp. 599-608, September 2015.

[70] M. N. Anwar, S. Pan and S. Ghosh, "PI controller design for pitch control of large wind turbine generator," *2015 International Conference on Energy, Power and Environment*: Towards Sustainable Growth (ICEPE), Shillong, pp. 1-6, 2015.

[71] Ramji Tiwari, N. Ramesh Babu, Recent developments of control strategies for wind energy conversion system, *Renewable and Sustainable Energy Reviews*, Volume 66, pp. 268-285, December 2016.

[72] Minh Quan Duong, Francesco Grimaccia, Sonia Leva, Marco Mussetta, Emanuele Ogliari, Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system, *Renewable Energy*, Volume 70, pp. 197-203, October 2014.

[73] Sasmita Behera, Bidyadhar Subudhi, Bibhuti Bhusan Pati, “Design of PI Controller in Pitch Control of Wind Turbine: A Comparison of PSO and PS Algorithm,” *International Journal of Renewable Energy Research*, vol. 6, No 1, pp 271-281, 2016.

[74] S. A. Taher and S. Mansouri, “Optimal PI controller design for active power in grid-connected SOFC DG system,” *International Journal of Electrical Power and Energy Systems*, Vol. 60, pp. 268–274, 2014.

[75] Iman Poultangari, R. Shahnazi and M. Sheikhan, “RBF neural network based PI pitch controller for a class of 5-MW wind turbines using particle swarm optimization algorithm,” *ISA Transactions* Vol.51, pp. 641–648, Sept. 2012.

[76] Minh Quan Duong, Francesco Grimaccia, Sonia Leva, Marco Mussetta, Emanuele Ogliari, Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system, *Renewable Energy*, Volume 70, pp. 197-203, Oct. 2014.

[77] R. Chedid, F. Mrad and M. Basma, "Intelligent control of a class of wind energy conversion systems," *IEEE Transactions on Energy Conversion*, vol. 14, no. 4, pp. 1597-1604, Dec. 1999.

[78] The Fuzzy Systems Handbook, Second Edition: A Practitioner's Guide to Building, Using, and Maintaining Fuzzy Systems 2nd Edition by Earl Cox (Author), Michael O'Hagan (Author) Academic press, 1998.

[79] T. L. Van, T. H. Nguyen and D. C. Lee, "Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems," *IEEE Transactions on Energy Conversion*, vol. 30, no. 2, pp. 578-587, June 2015.

[80] B. Han, L. Zhou, F. Yang and Z. Xiang, "Individual pitch controller based on fuzzy logic control for wind turbine load mitigation," *IET Renewable Power Generation*, vol. 10, no. 5, pp. 687-693, 2016.

[81] M.A. Chowdhury, “Smoothing wind power fluctuations by artificial neural network-based pitch angle controller,” *International Journal of Renewable Energy Technology*, vol. 6, no.3, 2015, pp. 276 – 294.

[82] Yilmaz, A.S. and Z. Ozer, Pitch angle control in wind turbines above the rated wind speed by multi-layer perceptron and radial basis function neural networks.

Expert Systems with Applications, 2009. 36(6): pp. 9767-9775.

[83] Md. Maruf Hossain and Mohd. Hasan Ali, “Future research directions for the wind generator system,” *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 481-489, Sept. 2015.

[84] Yaxing Ren, Liuying Li, Joseph Brindley, Lin Jiang, Nonlinear PI control for variable pitch wind turbine, *Control Engineering Practice*, vol. 50, pp. 84-94, May 2016.

[85] Abdeldjalil Dahbi, Nasreddine Nait-Said, Mohamed-Said Nait-Said, A novel combined MPPT-pitch angle control for wide range variable speed wind turbine based on neural network, *International Journal of Hydrogen Energy*, vol. 41, Issue 22, pp. 9427-9442, 15 June 2016.

[86] Z. Civelek, E. Çam, M. Lüy and H. Mamur, "Proportional–integral–derivative parameter optimisation of blade pitch controller in wind turbines by a new intelligent genetic algorithm," *IET Renewable Power Generation*, vol. 10, no. 8, pp. 1220-1228, 2016.

[87] H. Geng and G. Yang, "Robust pitch controller for output power levelling of variable-speed variable-pitch wind turbine generator systems," *IET Renewable Power Generation*, vol. 3, no. 2, pp. 168 -179, June 2009.

[88] S. Bououden, M. Chadli and H. R. Karimi, "Robust Predictive Control of a variable speed wind turbine using the LMI formalism," *2014 European Control Conference (ECC)*, Strasbourg, pp.820-825, 2014.

[89] Pedram Bagheri, Qiao Sun, Adaptive robust control of a class of non-affine variable-speed variable-pitch wind turbines with unmodeled dynamics, *ISA Transactions*, vol. 63, pp. 233-241, July 2016.

[90] H.M. Hassan, A.L. ElShafei, W.A. Farag, M.S. Saad, A robust LMI-based pitch controller for large wind turbines, Renewable Energy, vol. 44, pp. 63-71, Aug. 2012.

[91] Mazhar. H. Baloch, Jie Wang, and Ghulam. S. Kaloi , “A Review of the State of the Art Control Techniques for Wind Energy Conversion System’’ *International Journal of Renewable Energy Research*, Vol.6, No.4, pp. 1276-1295, 2016.

[92] H. Kasiri, H. R. Momeni, M. Azimi and A. R. Motavalian, "A new hybrid optimal control for WECS using MLP Neural Network and Genetic neuro Fuzzy," *The 2nd International Conference on Control, Instrumentation and Automation*, Shiraz, pp. 361-366, 2011.

[93] Minh Quan Duong, Francesco Grimaccia, Sonia Leva, Marco Mussetta, Emanuele Ogliari, Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system, *Renewable Energy*, vol.70, pp. 197-203, Oct. 2011.

[94] Whei-Min Lin, Chih-Ming Hong, Ting-Chia Ou, Tai-Ming Chiu, Hybrid intelligent control of PMSG wind generation system using pitch angle control with RBFN, *Energy Conversion and Management*, Volume 52, Issue 2, pp. 1244-1251, February 2011.

[95] Dipesh Kumar, Kalyan Chatterjee, A review of conventional and advanced MPPT algorithms for wind energy systems, *Renewable and Sustainable Energy Reviews*, Volume 55, pp. 957-970, Mar. 2016.

[96] S. Zahra Mirbagheri, Saad Mekhilef, S. Mohsen Mirhassani, MPPT with Inc.Cond Method using Conventional Interleaved Boost Converter, *Energy Procedia*, vol. 42, pp. 24-32, 2013.

[97] H. Yokoyama, F. Tatsuta and S. Nishikata, "Tip speed ratio control of wind turbine generating system connected in series," *2011 International Conference on Electrical Machines and Systems*, Beijing, pp. 1-4, 2011.

[98] M. Nasiri, J. Milimonfared, S.H. Fathi, Modeling, analysis and comparison of TSR and OTC methods for MPPT and power smoothing in permanent magnet synchronous generator-based wind turbines, *Energy Conversion and Management*, Volume 86, pp. 892-900 , Oct. 2014.

[99] M. Barakati, M. Kazerani and D. Aplevich, "Maximum power tracking control for a wind turbine system including a matrix converter," *2009 IEEE Power & Energy Society General Meeting*, Calgary,AB, pp.1-1, 2009.

[100] S. S. Kumar, K. Jayanthi and N. S. Kumar, "Maximum power point tracking for a PMSG based variable speed wind energy conversion system using optimal torque control," *2016 International Conference on Advanced Communication Control and Computing Technologies (ICACCCT)*, Ramanathapuram, India, pp. 347-352, 2016.

[101] M. Nasiri, J. Milimonfared, S.H. Fathi, Modeling, analysis and comparison of TSR and OTC methods for MPPT and power smoothing in permanent magnet synchronous generator-based wind turbines, *Energy Conversion and Management*, Volume 86, pp. 892-900, October 2014.

[102] J. Lee and Y. S. Kim, "Sensorless fuzzy-logic-based maximum power point tracking control for a small-scale wind power generation systems with a switched-

mode rectifier," *IET Renewable Power Generation*, vol. 10, no. 2, pp. 194-202, Feb. 2016.

[103] Saliha Arezki, and Mohamed Mohamed Boudour, “Solution to the Instability of DC Bus Voltages in Wind Chain Associate to DFIG with MPPT, ” *International Journal of Renewable Energy Research-IJRER*, vol. 2, no. 4, pp. 564-573, 2012.

[104] S. Marmouh, M. Boutoubat and L. Mokrani, "MPPT fuzzy logic controller of a wind energy conversion system based on a PMSG," *2016 8th International Conference on Modelling, Identification and Control (ICMIC)*, Algiers, pp. 296-302, 2016.

[105] C. Wei, L. Qu and W. Qiao, "Evaluation of ANN estimation-based MPPT control for a DFIG wind turbine," *2014 IEEE Symposium on Power Electronics and Machines for Wind and Water Applications*, Milwaukee, WI, pp. 1-6, 2014.

[106] Anil K. Rai, N.D. Kaushika, Bhupal Singh, Niti Agarwal, “Simulation model of ANN based maximum power point tracking controller for solar PV system,” *Solar Energy Materials and Solar Cells*, vol. 95, Issue 2, pp 773-778, February 2011.

[107] Mohammad Abu Jami, Imam Sutrisno and Jinglu Hu, “Maximum power tracking control for a wind energy conversion system based on a quasi-ARX neural network model, ” *Transaction of Electrical & Electronics Engineering*, vol. 10, Issue 4, pp. 368 375,July 2015.

[108] J. Hussain and M. K. Mishra, "Adaptive Maximum Power Point Tracking Control Algorithm for Wind Energy Conversion Systems," *IEEE Transactions on Energy Conversion*, vol. 31, no. 2, pp. 697-705, June 2016.

[109] A. Urtasun, P. Sanchis and L. Marroyo, "Small Wind Turbine Sensorless MPPT: Robustness Analysis and Lossless Approach," *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 4113-4121, Nov.-Dec.2014.

[110] Yacine Daili, Jean-Paul Gaubert, Lazhar Rahmani, Implementation of a new maximum power point tracking control strategy for small wind energy conversion systems without mechanical sensors, *Energy Conversion and Management*, vol. 97, pp. 298-306, June 2015.

[111] V. Nayanar, N. Kumaresan and N. Ammasai Gounden, "A Single-Sensor-Based MPPT Controller for Wind-Driven Induction Generators Supplying DC Microgrid," *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 1161-1172, Feb. 2016.

[112] C. Wei, Z. Zhang, W. Qiao and L. Qu, "An Adaptive Network-Based Reinforcement Learning Method for MPPT Control of PMSG Wind Energy Conversion Systems," *IEEE Transactions on Power Electronics*, vol. 31, no. 11, pp. 7837-7848, Nov. 2016.

[113] J. Lee and Y. S. Kim, "Sensorless fuzzy-logic-based maximum power point tracking control for a small-scale wind power generation systems with a switched-mode rectifier," *IET Renewable Power Generation*, vol.10, no.2, pp. 194-202 , 2016.

[114] J. Lee and Y. S. Kim, "Sensorless fuzzy-logic-based maximum power point tracking control for a small-scale wind power generation systems with a switched-mode rectifier," *IET Renewable Power Generation*, vol. 10, no. 2, pp. 194-202, Feb. 2016.

[115] Maryam Moazen , Rasool Kazemzade , Mohammad-Reza Azizian, “Power Control of BDFRG Variable-Speed Wind Turbine System Covering All Wind Velocity Ranges, ” *International journal of renewable energy research-IJRER*, vol.6, no. 2, pp. 477-486, 2016.

[116] Sami Kahla, Youcef Soufi, Moussa Sedraoui and Mohcene Bechouat, “Maximum Power Point Tracking of Wind Energy Conversion System Using Multi-objective grey wolf optimization of Fuzzy-Sliding Mode Controller,” *International Journal of Renewable Energy Research*, vol 7, no 2. pp. 926-936, 2017.

[117] Youssef Errami, Mohammed Ouassaid, Mohamed Cherkaoui, and Mohamed Maaroufi, “Maximum Power Point Tracking Control Based on a Nonlinear Backstepping Approach for a Permanent Magnet Synchronous Generator Wind Energy Conversion System Connected to a Utility Grid ,” *Energy Technology*, vol 3, no. 7, pp. 743-757, June 2015.

[118] J. W. Choi, S. Y. Heo and M. K. Kim, "Hybrid operation strategy of wind energy storage system for power grid frequency regulation," in *IET Generation, Transmission & Distribution*, vol. 10, no. 3, pp. 736-749, 2016.

[119] C. Busca, A. I. Stan, T. Stanciu and D. I. Stroe, "Control of Permanent Magnet Synchronous Generator for large wind turbines," *2010 IEEE International Symposium on Industrial Electronics*, Bari, pp. 3871-3876, 2010.

[120] Model Predictive Control of Wind Energy Conversion Systems, Venkata Yaramasu, Bin Wu John Wiley & Sons, 14-Dec-2016.

[121] Djamila Rekioua, Wind Power Electric Systems: Modeling, Simulation and Control.

[122] Mehdi Allagui, OthmanBk Hasnaoui & Jamel Belhadj, “A 2MW direct drive wind turbine; vector control and direct torque control techniques comparison,” *Journal of Energy in Southern Africa*, Vol 25, no 2, pp. 117-126, May 2014.

[123] T. K. A. Brekken and N. Mohan, "Control of a Doubly Fed Induction Wind Generator Under Unbalanced Grid Voltage Conditions," *IEEE Transactions on Energy Conversion*, vol. 22, no. 1, pp. 129-135, March 2007.

[124] L. Xu and Y.Wang, “Dynamic modeling and control of DFIG-based wind turbines under unbalanced network conditions,” IEEE Trans. Power Syst., vol. 22, no. 1, pp. 314–323, Feb. 2007.

[125] G. Abad, M. Á. Rodríguez, G. Iwanski and J. Poza, "Direct Power Control of Doubly-Fed-Induction-Generator-Based Wind Turbines Under Unbalanced Grid Voltage," *IEEE Transactions on Power Electronics*, vol. 25, no. 2, pp. 442-452, Feb. 2010.

[126] Phan, V.-T., Lee, H.-H. “Improved predictive current control for unbalanced stand-alone doubly-fed induction generator-based wind power systems,” IET Electr. Power Appl. vol. 5, no.3, pp. 275–287, 2011.

[127] Martinez, M.I., Susperregui, A., Tapia, G., Xu, L. “Sliding-mode control of a wind turbine-driven double-fed induction generator under non-ideal grid voltages”, IET Renew. Power Gener, vol.7, no. 4, pp. 370–379, 2013.

[128] J. Hu, J. Zhu and D. G. Dorrell, "Predictive Direct Power Control of Doubly Fed Induction Generators Under Unbalanced Grid Voltage Conditions for Power Quality Improvement," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 943-950, July 2015.

[129] X. Yuan *et. al*., “DC-link voltage control of a full power converter for wind generator operating in weak-grid systems,” *IEEE Trans. Power Electron.*, vol. 24, no. 9, pp. 2178–2192, Sep. 2009.

[130] Mike Woebbeking, The new guideline for the certification of wind turbines, 2010.

[131] Guideline for the Certification of Wind Turbines, Rules and Guidelines Industrial Services, Germanischer Llyod(GL), 2010.

[132] IEC webstore: https://webstore.iec.ch/searchform