Abstract
Wind power production has been under the main focus for the past decade in power production and tremendous amount of research work is going on renewable energy, specifically on wind power extraction. Wind power provides an eco-friendly power generation and helps to meet the national energy demand when there is a diminishing trend in terms of non-renewable resources. This paper reviews the modeling of Wind Energy Conversion Systems (WECS), control strategies of controllers and various Maximum Power Point Tracking (MPPT) technologies that are being proposed for efficient production of wind energy from the available resource.

Keywords: Wind energy, Conversion systems, Maximum power, Induction generator, Permanent magnet, Wind turbine.

1. Introduction
The wind energy conversion system (WECS) includes wind turbines, generators, control system, interconnection apparatus. Wind Turbines are mainly classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Modern wind turbines use HAWT with two or three blades and operate either downwind or upwind configuration. This HAWT can be designed for a constant speed application or for the variable speed operation. Among these two types variable speed wind turbine [1] has high efficiency with reduced mechanical stress and less noise. Variable speed turbines produce more power than constant speed type, comparatively, but it needs sophisticated power converters [2, 3], control equipments to provide fixed frequency and constant power factor [4].
The generators used for the wind energy conversion system mostly of either doubly fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG) type. DFIG have windings on both stationary and rotating parts, where both windings transfer significant power between shaft and grid. In DFIG the converters have to process only about 25-30 percent of total generated power (rotor power connected to grid through converter) and the rest being fed to grid directly from stator. Whereas, converter used in PMSG has to process 100 percent power generated, where 100 percent refers to the standard WECS equipment with three stage gear box in DFIG. Majority of wind turbine manufacturers utilize DFIG for their WECS due to the advantage in terms of cost, weight and size. But the reliability associated with gearbox, the slip rings and brushes in DFIG is unsuitable for certain applications. PMSG does not need a gear box and hence, it has high efficiency with less maintenance [3, 5-9]. The PMSG drives achieve very high torque at low speeds with less noise and require no external excitation. In the present trend WECS with multibrid [10, 11] concept is interesting and offers the same advantage for large systems in future. Multibrid is a technology where generator, gearbox, main shaft and shaft bearing are all integrated within a common housing. This concept allows reduce in weight and size of generators combined with the gear box technology. The generators with multibrid concept become cheaper and more reliable than that of the standard one, but it loses its efficiency.

To achieve high efficient energy conversion on these drives different control strategies can be implemented like direct torque control (DTC) [12], field oriented control (FOC) [13]. The FOC using PI controller has linear regulation and the tuning becomes easier. The wind turbine electrical and mechanical parts are mostly linear and modeling will be easier. The blade aerodynamics of the wind turbine is a nonlinear one and hence the overall system model will become nonlinear. The wind energy conversion system which will be modeled as shown in Fig. 1 may not be optimal for extracting maximum energy from the resource and hence various optimization techniques are used to achieve the goal.

2. WECS modeling

The basic device in the wind energy conversion system is the wind turbine which transfers the kinetic energy into a mechanical energy. The wind turbine is connected to the electrical generator through a coupling device gear train. The output of the generator is given to the electrical grid by employing a proper controller to avoid the disturbances and to protect the system or network. Figure 1
shows the overall block diagram of the wind energy conversion system (WECS). Here, \( V_n \), represents wind speed, \( P_w \), \( P_m \) and \( P_e \) represent wind power, mechanical power and electrical power respectively.

![WECS Block Diagram](image)

**Fig. 1. WECS Block Diagram.**

### 2.1. Wind turbine

Wind energy is transformed into mechanical power through wind turbine and hence it is converted into electrical power. The mechanical power is calculated by using the following equation [13],

\[
P_m = 0.5 \rho A C_p(\lambda, \beta) \nu_{wind}^3
\]  

(1)

where, \( \rho \) is the air density which normally takes the value in the range 1.22-1.3 kg/m\(^3\), \( A \) is the area swept out by turbine blades (m\(^2\)), \( \nu_{wind} \) is the wind speed (m/s), \( C_p(\lambda, \beta) \) is the power coefficient [14-17] which depends on two factors: \( \beta \), the blade pitch angle and the tip speed ratio and, \( \lambda \), which is defined as:

\[
\lambda = \frac{\Omega R}{\nu_{wind}}
\]  

(2)

where, \( \Omega \) is the angular speed (m/s) and \( R \) is the blade radius (m).

The power coefficient, \( C_p \) is defined as

\[
C_p(\lambda, \beta) = C_1 \left( \frac{C_{\lambda}}{\lambda} - C_2 \beta - C_3 \right) \exp \left( -\frac{C_4}{\lambda} \right) + C_5 \lambda
\]  

(3)

where

\[
\frac{1}{\lambda_1} = \left( \frac{1}{\lambda + 0.08 \beta} \right) - \frac{0.035}{\beta^3 + 1}
\]

and coefficients \( C_1 = 0.5176 \), \( C_2 = 116 \), \( C_3 = 0.4 \), \( C_4 = 5 \), \( C_5 = 21 \), and \( C_6 = 0.0068 \).

The power coefficient is nonlinear, and it depends upon turbine blade aerodynamics and it can be represented as a function of tip speed ratio, \( \lambda \). The optimum value of \( \lambda \) corresponds to maximum of \( C_p \) from the power coefficient-tip speed ratio curve.

Figure 2 shows the power coefficient with respect to tip speed ratio. It is observed that the maximum power coefficient value \( C_{p,\text{max}}(\lambda, \beta) = 0.48 \) for \( \lambda = 12 \) and \( \beta = 0^\circ \). This particular value of \( \lambda_{\text{opt}} \) results in optimal efficiency point where maximum power is captured from wind by the turbine.
Fig. 2. Power Coefficient of the Wind Turbine Model [13].

As the power transmitted is assumed to be the product of rotational speed with mechanical torque, the rotational torque is obtained as:

$$T_m = \frac{P_m}{\Omega}$$  \hspace{1cm} (4)

Thus the optimal angular speed is achieved through the relation,

$$\Omega_{opt} = \frac{\lambda_{opt} \nu_{wind}}{R}$$  \hspace{1cm} (5)

and the maximum mechanical power is,

$$P_{m, max} = 0.5 \mu A_{c} C_{p, max} \nu_{wind}^3$$  \hspace{1cm} (6)

Figure 3 shows the wind turbine power characteristics obtained for various values of the wind tangential speed [18]. Here it can be observed that maximum power (active) is achieved through optimal wind speeds and not at high wind velocity. The wind turbine does not operate when the wind speed is less than the minimum speed because the captured wind energy is not enough to compensate the losses and operation cost.

Fig. 3. Wind Turbine Power Characteristics [18].
2.2. Drive train modeling

The gear box enables to convert the slow speed of the turbine blades to high speed required by the electrical machine through the gear box ratio, \( g_r \). This element converts the mechanical torque and the machine speed as follows \[19\]:

\[
T_{\text{aero}} = g_r \cdot T_m \tag{7}
\]

\[
\Omega_m = g_r \cdot \Omega \tag{8}
\]

where, \( T_{\text{aero}} \) is the aerodynamic torque and \( \Omega_m \) is the machine speed. The drive train is modeled by the simplified motion equation as follows:

\[
J \frac{d\Omega}{dt} = T_m - T_e - f \cdot \Omega_m \tag{9}
\]

where \( J \) is the mechanical inertia of the wind turbine and generator, \( T_e \) is the electromagnetic torque, and \( f \) is the friction coefficient.

2.3. PMSG modeling

The modeling of PMSG type electrical equipment is made through the following equations, represented by d-q reference frame \[19\]:

\[
V_d = R_i i_d + L_d \frac{di_d}{dt} - \omega_s L_q i_q
\]

\[
V_q = R_i i_q + L_q \frac{di_q}{dt} - \omega_s L_d i_d + \omega_s \varphi_m \tag{11}
\]

where \( V_d \) and \( V_q \) are d and q components of stator voltages (V), \( i_d \) and \( i_q \) are d and q components of stator currents (A), \( R_i \) is stator resistance (ohms), \( L_d \) and \( L_q \) are machine inductances (H), \( \omega_s \) is the electrical speed (rad/s) and \( \varphi_m \) is the magnetic flux (wb). The electrical torque is obtained through the following equation:

\[
T_e = \frac{3}{2} p \left( \varphi_m i_q + (L_d - L_q) i_d i_q \right) \tag{12}
\]

where \( p \) is the pair of poles. The rotor dynamics of the machine is given by

\[
T_m - T_e = B \omega_r + J \frac{d\omega_r}{dt} \tag{13}
\]

where \( B \) is the rotor friction (kgm^2/s), \( J \) is the rotor inertia (kgm^2), \( \omega_r \) is rotor speed (rad/s) and \( T_m \) is the mechanical torque produced by wind (Nm). The machine dynamics can be simplified by assuming \( (L_d = L_q = 0) \) and the d-reference current is zero \( (i_d^* = 0) \) and hence the product term \( (L_d \cdot L_q) i_d i_q \) is negligible. More information about the PMSG modeling is presented in \[20\-22\].

2.4. DFIG modeling

The commonly used model for induction generator is the Park model \[20\]. To obtain its state model we neglect stator resistance, and then we have:

\[
\Phi_{sq} = 0, \quad \frac{d\Phi_{dq}}{dt} = 0, \quad V_{sd} = 0 \quad \text{and} \quad V_{sq} = - V_s
\]
where $V_s$ is the stator voltage. The reduced state model [23] is obtained as follows:

$$V_{rd} = \sigma L_r \frac{di_{rd}}{dt} + r_r i_{rd} - (\omega_s - \Omega) \sigma L_r i_{rq}$$  \hspace{1cm} (14)$$

$$V_{rq} = \sigma L_r \frac{di_{rq}}{dt} + r_r i_{rq} + (\omega_s - \Omega) \sigma L_r i_{rd} + \frac{M}{L_s} \Phi_{sd} (\omega_s - \Omega)$$  \hspace{1cm} (15)$$

where $V_{rd}$ and $V_{rq}$ are the $d$ and $q$ components of rotor voltage ($V$), $i_{rd}$ and $i_{rq}$ are the $d$ and $q$ components of rotor current ($A$), $\Phi_{sd}$ and $\Phi_{sq}$ are the $d$ and $q$ components of stator flux (wb), $\omega_s$ is the synchronous pulsation, $\Omega$ is the generator speed, $r_r$ is the rotor resistance, $L_s$ and $L_r$ are the stator and rotor inductances (H), $M$ is the mutual inductance (H) and $\sigma$ is the leakage parameter given as, $\sigma = 1 - (M^2/L_s L_r)$. More information about stand-alone and/or grid connected operation of DFIG is presented in papers [24-27].

DFIG is one of the most important generators and are widely used for variable speed WECS. Nowadays, this type of DFIG-WECS has a part of wind energy market, which is close to 50%. Major wind turbine producers manufacture wind energy conversion system based on DFIG’s but the difficulties associated in complying with grid side ride-through requirement may limit its use in future [28, 29]. To overcome the above stated difficulty, PMSG technology looks most promising in WECS, which shares nearly 45% in wind energy market. Multi-pole PMSG’s with full power back-to-back converters appears to be the configuration to be adapted by most of the wind turbine manufacturers in near future, gradually replacing DFIG in wind energy market. Wind energy conversion systems with the range of 1.5 MW to 3 MW are manufactured by 44 companies in 163 models. Among these 60 models uses DFIG, 66 models uses PMSG, 18 models uses cage type IG and 19 models uses synchronous generator with external excitation [5].

3. Control Strategies

3.1. DFIG-WECS control

Controller is designed to adjust the turbine speed to extract the maximum power from wind source. Usually PI controller is designed for this purpose according to the estimated parameters either offline or online and the observed disturbance torque is feed forward to increase system robustness. But this type of classical controller is not enough to serve the purpose efficiently. Hence various improvements are made for the controller to achieve the requirement as stated below.

The general structure of control block diagram in the DFIG-WECS having two levels of control is shown in Fig. 4. The highest level is WECS optimization which is explained in section IV. The lower level control being the electrical control system, i.e. torque and reactive power control. The rotor side controller (RSC) and grid side controller (GSC) are employed to serve the electrical control system. To compromise the dynamics of variable speed WECS Poitiers et al. [30] has implemented a two degree freedom Regulation-Solution-Tracking (R-S-T) controller, which is a widely preferred digital controller and Linear Quadratic
Gaussian (LQG) controller with state feedback. For the ease of implementation of controller tuning the LQG controller is preferred than R-S-T controller.

To reduce the output power fluctuations of DFIG with a flywheel energy storage system (FESS) Jerbi et al. [31-33] has proposed a fuzzy supervisor using sugeno fuzzy model based on two parameters flywheel speed and wind power accessibility so as to ensure a smooth reactive power to the load supplied by the wind generator [19]. This ensures to reduce the voltage fluctuations. For the variable speed WECS [34] has proposed a method which will combine fuzzy neural network and sliding mode speed observer. This technique allows faster convergence to a simple linear dynamic behavior, even in presence of parameter changes and uncertainties which are the major problems expected from variable speed drive control. As most of the controllers depends on torque control M. Pucci [15] proposes a method based on speed control of the machine. This is achieved through total least squares (TLS) EXIN full order observer [35] which turns as an intelligent sensor less technique for wind generation control.

![Control Block Diagram of DFIG Based WECS](image)

**Fig. 4. Control Block Diagram of DFIG Based WECS [30].**

There are other types of controllers using PID for controlling the WECS with optimal power output. Muhando et.al proposes a self-tuning regulator [17] by incorporating recursive least square algorithm to predict the process parameters and update the states. This regulator gives more efficient compared to classical PID controller. To achieve optimal power, adaptive fuzzy PID control strategies are proposed [36] and proved the performance is improved than that of conventional one.

Many research papers discuss the intelligent controllers with sensor less [37] wind energy control. Wei-Min Lin et al. [38] proposed a technique where design is made online through recurrent fuzzy neural controller (RFNN) with high performance model reference adaptive system (MRAS) observer which replaces the use of sensors to measure the parameters. Lin et.al suggested that to increase the learning ability of back propagation network of RFNN modified particle swarm
optimization is used (mPSO). This provides fast and accurate velocity information to avoid anemometers and rotor position is estimated from flux linkages.

Behra and Rao [39] investigated novel grid side controller, modeled in synchronously rotating reference frame to improve the dynamic response on various load conditions. Liu and Hsu [40] discuss the stator resistance effect on the excitation voltage, which gives the maximum output power and minimal loss for the DFIG. The DFIG-WECS model can be validated through various simulation tools. To improve the real time simulation time FPGA’s can be incorporated using Runge-Kutta numerical integration algorithm [41] in compared to PC based simulation.

3.2. PMSG-WECS control

Figure 5 shows the block diagram of PMSG based WECS with two stages as optimization and electrical controllers. The various techniques are discussed as below.

Jordi Zaragoza et al. [13] discusses the control of PMSG based WECS using field oriented control (FOC) for controlling speed regulation and generating current. A PI controller is used for this purpose and the tuning parameters are determined through zero-pole cancellation (ZPC) strategy. Jemaa Brahmi et.al [42] compares three control methods for PMSG based WECS. In the first model MRAS observer is used to estimate the parameters of the controller by comparing output of reference model and adaptive model. Secondly artificial neural network (ANN) based observer were trained to produce desired output correction to the estimated speed. And firstly, sliding mode observer (SMO) based control is discussed. Among these three techniques SMO and ANN observer gives good results when static resistance varies and chattering phenomenon is observed with SMO. The static resistance causes a static error in case of MRAS observer. The SMO is more robust than the other two methods.
Kelvin Tan and Syed Islam [43] proposed a sensor less optimal control strategy using fuzzy power mapping technique. Using the result of power mapping loop and alternator frequency derivative loop, the controller allows the bus voltage to vary to maximum power operating point. Bao et al. [44] proposes an adaptive control strategy [45] for variable speed wind turbine using neural based identifier [46] and inverse model controller which has good learning capability and high performance than nonlinear controller. Wang et al proposes indirect matrix converter of PID [47] type which has more degree of freedom and can be implemented in an easy way for the PMSG based WECS. This shows excellent dynamic performances with lower mechanical stress [48] and robust in control.

There are other techniques for controlling the WECS [49]. Wind prediction control scheme is the one where the control parameters are obtained through forecasting the wind using autoregressive statistical models. This method will avoid the mechanical sensors used to get the actual parameter tracking.

4. Optimization of WECS

The next challenging task in WECS is to operate the system at the optimal point so as to increase the output. The optimization block is shown in Figs. 4 and for DFIG and PMSG based WECS. Among the various techniques followed for this, maximum power point tracking (MPPT) [50] plays a vital role.

Kesraoui et al. [51] proposed the MPPT algorithm using step and search method to extract the maximum power from the wind turbine from cut-in to rated wind velocity by sensing the dc link power. Iulian Munteanu et al. [52] used wind turbulence as a search for MPPT instead of sinusoidal search. Here high speed shaft’s average speed is slowly adjusted using FFT of measures from system as an estimate to the optimal point. This method is effective when the wind turbulence level is high. The same author also proposes sliding mode control [53], optimal regime tracking [54, 55], and frequency separation principle [56] for optimizing the WECS based on PMSG type. Syed Muhammad et al. [57] proposes a novel method of MPPT along with Hill Climb Search (HCS) algorithm [58]. This method performs self-tuning to cope with the non-constant efficiency of the generator-converter systems. This paper ensures high control efficiency and faster tracking under rapid wind change without requiring any prior knowledge of system characteristics.

Adaptive neuro fuzzy inference system (ANFIS) based MPPT is discussed in Meharrar et al. [59]. Here variation of wind speed is used as input for ANFIS to predict optimal speed rotation and back propagation learning algorithm is used for training this network. This method shows better response than compared to FLC. Other type of fuzzy controller was proposed by Calderaro et al. [60] using Takagi-Sugeno-Kang (TSK) model to maximize energy extraction which avoids sensors in MPPT. To estimate the optimum value for generator support vector regression (SVR) algorithm is used by Lee et al. [61]. It is proved that the generator losses are reduced up to 40% and also excellent in accuracy. Kazmi et al. [15] proposes growing neural gas (GNG) based MPPT which is having FOC integrated with TLS EXIN observer without sensors to optimize the system.

A new method of MPPT which uses gradient approximation algorithm is proposed by Ying-Yi Hong et al. [62]. This method does not require anemometer,
tachometer and information of wind turbine generator system characteristics. As the gradient approximation converges very fast and the implementation is easy, this method is efficient for an optimization problem. Kongnam and Nuchprayoon [63] propose to apply PSO to solve for optimum rotor speed in fixed and variable speed operation of WECS. In this power and energy are more dependent of mean wind speed than weibull distribution of speed.

Pitch angle control of wind turbine turns out to be another optimization problem in WECS [64, 65]. Yilmaz and Zafer [66] discusses radial basis function based neural network controller which tracks the reference signal based on training to achieve better controller. Boukhezzar et al. [67] propose control strategy by combining torque control and pitch control which leads to good performance in rotor speed regulation and electrical power regulation with acceptable control loads compared to classical PID and LQG controllers.

5. Conclusions

An attempt has been made in this paper to discuss the most-recent research trends in the field of wind energy conversion systems. From the study, it can be concluded that in case of generators and converters, most system adopts DFIG with back-to-back converter due to their less weight and cost. However, for the large capacity wind turbines where efficiency and reliability plays a major role has been utilizing PMSG’s even though it has more weight and increased installation cost. Moreover, WECS based on the multibrid concept, will become more attractive alternative technology in the future.

Regarding the controllers for the WECS, is still the most important and challenging topic of research as there are various controllers had been proposed by various researchers has been discussed in this paper. As there are lot of ongoing developments takes place at various stages of WECS, it is noted that the most suitable (optimized) solutions to extract maximum power of the installed system is ad-hoc, rather than generalized solution.

The overview of this information highlights the current research progress in the field of wind energy conversion system and this will be helpful for the new researchers to focus on the above area.

References


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