TO EXTRACT THE MAXIMUM POWER USING UTILITY-INTERFACED WIND TURBINE MODEL

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Abstract- **Maximum power extraction from wind energy system became an important research topic due to the increase in output energy by using this technique. Wind speed sensorless MPPT control has been a very active area of research. The WT is connected to the grid via back–to-back PWM-VSC. The generator side controller and the grid side controller have been done in Simulink. The main function of the generator side controller is to track the maximum power from wind through controlling the rotational speed of the turbine using fuzzy logic controller. The fuzzy logic algorithm for the maximum output power of the grid-connected wind power generation system using a PMSG has been proposed and implemented above. The PMSG was controlled in indirect-vector field oriented control method and its speed reference was determined using fuzzy logic controller. A co-simulation (PSIM/Simulink) program has been proposed for WECS where PSIM contains the power circuit of the WECS and Matlab/Simulink has the control circuit of the system.**

Keywords— PMSG, Fuzzy logic controller, Wind Turbine model

I.INTRODUCTION

Wind energy is one of the most promising renewable energy resources for producing electricity due to its cost competitiveness compared to other conventional types of energy resources. It takes a particular place to be the most suitable renewable energy resources for electricity production. It isn't harmful to the environment and it is an abundant resource available in nature. Hence, wind power could be utilized by mechanically converting it to electrical power using wind turbine, WT. Various WT concepts have a quick development of wind power technologies and significant growth of wind power capacity during last two decades. Variable speed operation and direct drive WTs have been the modern developments in the technology of wind energy conversion system, WECS. Variable-speed operation has many advantages over fixed-speed generation such as increased energy capture, operation at MPPT over a wide range of wind speeds, high power quality, reduced mechanical stresses, aerodynamic noise improved system reliability, and it can provide (10-15) % higher output power and has less mechanical stresses in comparison with the operation at a fixed speed [1, 2]. WTs can be classified according to the type of drive train into direct drive (DD) and gear drive (GD). The
GD type uses a gear box, squirrel cage induction generator (SCIG) and classified as stall, active stall and pitch control WT and work in constant speed applications. The variable speed WT uses doubly-fed induction generator, (DFIG) especially in high power WTs. The gearless DD WTs have been used with small and medium size WTs employing permanent-magnet synchronous generator (PMSG) with higher numbers of poles to eliminate the need for gearbox which can be translated to higher efficiency. PMSG appears more and more attractive, because the advantages of permanent magnet, (PM) machines over electrically excited machines such as its higher efficiency, higher energy yield, no additional power supply for the magnet field excitation and higher reliability due to the absence of mechanical components such as slip rings. In addition, the performance of PM materials is improving, and the cost is decreasing in recent years. Therefore, these advantages make direct-drive PM wind turbine systems more attractive in application of small and medium-scale wind turbines [1, 3-4].

Robust controller has been developed in many literatures [5-15] to track the maximum power available in the wind. They include tip speed ratio (TSR) [5, 13], power signal feedback (PSF) [8, 14], and the hill-climb searching (HCS) [11-12] methods. The TSR control method regulates the rotational speed of the generator to maintain an optimal TSR at which power extracted is maximum [13]. For TSR calculation, both the wind speed and turbine speed need to be measured, and the optimal TSR must be given to the controller. The first barrier to implement TSR control is the wind speed measurement, which adds to system cost and presents difficulties in practical implementations. The second barrier is the need to obtain the optimal value of TSR, this value is different from one system to another. This depends on the turbine-generator characteristics results in custom-designed control software tailored for individual wind turbines [14]. In PSF control [8, 14], it is required to have the knowledge of the wind turbine's maximum power curve, and track this curve through its control mechanisms. The power curves need to be obtained via simulations or off-line experiment on individual wind turbines or from the datasheet of WT which makes it difficult to implement with accuracy in practical applications [7-8, 15]. The HCS technique does not require the data of wind, generator speeds and the turbine characteristics. But, this method works well only for very small wind turbine inertia. For large inertia wind turbines, the system output power is interlaced with the turbine mechanical power and rate of change in the mechanically stored energy, which often renders the HCS method ineffective [11-12]. On the other hand, different algorithms have been used for maximum power extraction from WT in addition to the three method mentioned above. For example, Reference [1] presents an algorithm for maximum power extraction and reactive power control of an inverter through the power angle, δ of the inverter terminal voltage and the modulation index, m_a based variable-speed WT without wind speed sensor. Reference [16] presents an algorithm for MPPT via controlling the generator torque through q-axis current and hence controlling the generator speed with variation of the wind speed. These techniques are used for a decoupled control of the active and reactive power from the WT through q-axis and d-axis current respectively. Also, reference [17] presents a decoupled control of the active and reactive power from the WT, independently through q-axis and d-axis current but maximum power point operation of turbine system has been produced through regulating the input dc current of the dc/dc boost converter to follow the optimized current reference [17]. Reference [18] presents an algorithm for MPPT through directly adjusting duty ratio of the dc/dc boost converter and modulation index of the PWM-VSC. Reference [19] presents MPPT control algorithm based on measuring the dc-link voltage and current of the uncontrolled rectifier to attain the maximum available power from wind. Finally, references [20-22] present MPPT control based on a fuzzy logic control (FLC). The function of FLC is to track the generator speed with the reference speed for maximum power extraction at variable speeds. The MPPT algorithms can be divided into two categories, the first one is MPPT algorithms for WT with wind speed sensor and the second one is MPPT algorithms without wind speed sensor (sensorless MPPT controller). Wind speed sensor normally used in conventional wind energy conversion systems, WECS [10, 23] for implementing MPPT control algorithm. This algorithm increases cost and reduces the reliability of the WECS in addition to inaccuracies in measuring the wind speed. Therefore, some MPPT control methods estimate the wind speed; however, many of them require the knowledge of air density and mechanical parameters of the WECS [88-92]. Such methods require turbine generator characteristics result in custom-design software tailored for individual wind turbines. Air density, on the other hand, depends upon climatic conditions and may vary considerably over various seasons. Therefore, this technique is not favorite in modern design of WT and a lot of research efforts are focused on developing wind speed sensorless MPPT controller which does not require the knowledge of air density and turbine mechanical parameters [1, 9-11, 22-25]. Therefore, the cost and maintenance of the power control system is decreased and implementation of the power control system is not difficult compared to the sensored MPPT controller.

II. WIND ENERGY CONVERSION SYSTEMS

Figure 1 shows the schematic diagram of the variable-speed wind energy conversion system based on a synchronous generator. This system is directly connected to the grid through power conversion system. There are two common types of the power conversion systems, the first configuration is a back-to-back PWM-VSC connected to the grid. This configuration has a lot of switches, which cause more losses and voltage stress in addition to the presence of Electromagnetic Interference (EMI). The presence of a dc-link capacitor in PWM-VSC system provides a decoupling between the two converters, it separates the control between these two converters, allowing compensation of asymmetry of both on the generator side and on the grid side, independently [16]. The second configuration consists of a diode-bridge rectifier, a boost converter and a PWM-VSC connected to the grid. This configuration is, simple, less expensive, robust, and rigid and needs simple control system. But, with this configuration the control of the generator power factor is not possible, which in turn, affects generator efficiency. Also, high harmonic distortion currents are obtained in the generator that reduce efficiency and produce torque oscillations [22].

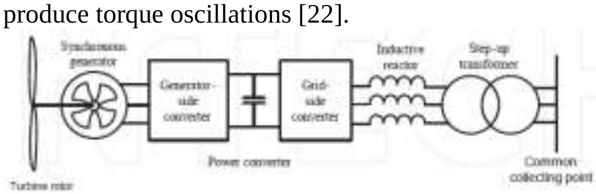

Fig 1: Wind energy conversion system based on synchronous generator

Wind turbine converts the wind power to a mechanical power, which in turn, runs a generator to generate electrical power. The mechanical power generated by wind turbine can be expressed as [15]:
The rotor aerodynamics are presented by the well-known static relations

$$P_W = c_P \frac{1}{2} \rho A {v_W}^3 \qquad (1)$$

Where, P is the power extracted from the wind [W]
ρ is the air Grid density
c_P is the power coefficient
$v_W$is thewind speed upstream of the rotor [m/s] and
A is the area swept by the rotor [m^2] (A=πR^2, being R the radius of the blade [m]).
The amount of aerodynamic torque (τ_w) in Nm is given by the ratio between the power extracted from the wind (P_w), in W, and the turbine rotor speed (ω_w), in rad/s, as follows equation

$$\tau_w = \frac{P_W}{\omega_W} \qquad (2)$$

The general function defining the power coefficient (c_P) as a function of the tip-speed ratio and the blade pitch angle is defined as

$$c_p(\lambda, \vartheta) = c_1\left(c_2 \frac{1}{\beta} - c_3\vartheta - c_4\vartheta^x - c_5\right) e^{-c_6 \frac{1}{\beta}} \qquad (3)$$

The parameter$\frac{1}{\beta}$ is defined by

$$\frac{1}{\beta} = \frac{1}{\lambda + 0.08\vartheta} - \frac{0.035}{1+\vartheta^3} \qquad (4)$$

Where ϑ is the pitch angle [°]
The tip-speed ratio λ is defined as

$$\lambda = \frac{\omega_w R}{v_w} \qquad (5)$$

Where ω_w is the angular velocity of rotor [rad/s], R is the rotor radius [m] and $v_W$is the wind speed upstream of the rotor [m/s].

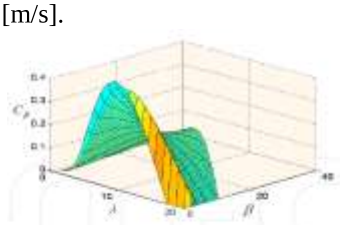

Fig 2. Aerodynamic power coefficient variation against λ and β.

III. MPPT CONTROL STRATEGIES FOR THE WECS

WECS has been attracting wide attention as a renewable energy source due to depleting fossil fuel reserves and environmental concerns as a direct consequence of using fossil fuel and nuclear energy sources. Wind energy varies continually as wind speed changes throughout the day, even though abundant. The Amount of power output from a WECS depends upon the accuracy of tracking the peak power points using the MPPT controller irrespective of the generator type used. The maximum power extraction algorithms can be classified into two categories. The two categories are MPPT algorithms with wind speed sensor and MPPT algorithms without wind speed sensor (sensor-less MPPT controller). These two algorithms have been discussed in the following sections.

A. Tip Speed Ratio (TSR) technique

The TSR control method regulates the rotational speed of the generator to maintain an optimal TSR at which power extracted is maximum [13]. The target optimum power extracted from wind turbine can be written as [14]:

$$P\max = K_{opt} {*} W_{opt} \qquad (6)$$

Where $K_{opt} = 0.5 * \rho A * \left(\frac{r_m}{\lambda_{opt}}\right)^3 * C_{p-\max}$, and

$$\omega_{opt} = \frac{\lambda_{opt}}{r_m} * u$$

The power for a certain wind speed is maximum at a certain value of rotational speed called optimum rotational speed, ω_{opt}. This optimum rotational speed corresponds to optimum tip speed ratio, λ_{opt}. In order to track maximum possible power, the turbine should always operate at λ_{opt}. This is achieved by controlling the rotational speed of the WT so that it always rotates at the optimum rotational speed. As shown in Figure 5, for TSR calculation, both the wind speed and turbine speed need to be measured, and the optimal TSR must be given to the controller. The first barrier to implement TSR control is the wind speed measurement, which adds to system cost and presents difficulties in practical implementations. The second barrier is the need to obtain the optimal value of TSR, this value is different from one system to another. This depends on the turbine-generator characteristics results in custom-designed control software tailored for individual wind turbines [14].

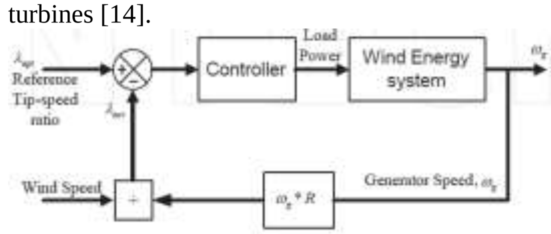

Fig 3. The block diagram of the tip speed ratio control of WECS

B. Power Signal Feedback (PSF) control

In PSF control [14], it is required to have the knowledge of the wind turbine's maximum power curve, and track this curve through its control mechanisms. The maximum power curves need to be obtained via simulations or off-line experiment on individual wind turbines or from the datasheet of WT which makes it difficult to implement with accuracy in practical applications. In this method, reference power is generated using a maximum power data curve or using the mechanical power equation of the wind turbine where wind speed or the rotational speed is used as the input. Figure 3 shows the block diagram of a WECS with PSF controller for maximum power extraction. The PSF control block generates the optimal power command P_{opt} which is then applied to the grid side converter control system for maximum power extraction as follow [15]:

$$P_{opt} = K_{opt} * \omega_r^3 \quad (7)$$

The actual power output, P_t is compared to the optimal power, P_{opt} and any mismatch is used by the fuzzy logic controller to change the modulation index of the grid side converter, PWMVSC as shown in Figure 4. The PWM-VSC is used to interface the WT with the electrical utility and will be controlled through the power angle, δ and modulation index, m_a to control the active and reactive power output from the WTG [15].

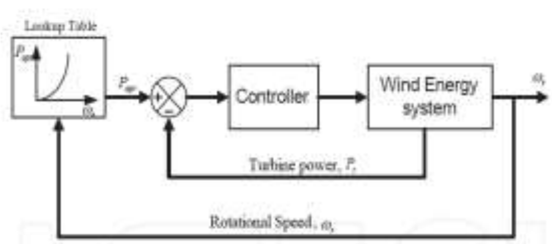

Fig 4. The block diagram of power signal feedback control

C. Optimal torque control

The aim of the torque controller is to optimize the efficiency of wind energy capture in a wide range of wind velocities, keeping the power generated by the machine equal to the optimal defined value. It can be observed from the block diagram represented in Figure 5, that the idea of this method is to adjust the PMSG torque according to the optimal reference torque of the wind turbine at a given wind speed. A typical wind turbine characteristic with the optimal torque-speed curve plotted to intersect the $C_{p\text{-}max}$ points for each wind speed is illustrated in Figure 6. The curve T_{opt} defines the optimal torque of the device (i.e. maximum energy capture), and the control objective is to keep the turbine on this curve as the wind speed varies. For any wind speed, the MPPT device imposes a torque reference able to extract the maximum power. The curve T_{opt} is defined by [20]:

$$T_{opt} = K_{opt} * \omega_{opt}^2 \quad (7)$$

where

$$K_{opt} = 0.5 * \rho A * \left(\frac{r_m}{\lambda_{opt}} \right)^3 * C_{p-max} \quad (8)$$

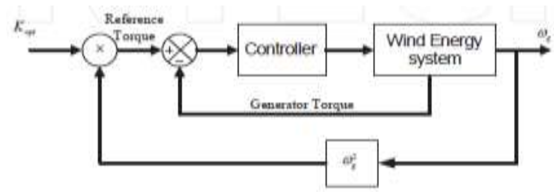

Fig 5. The block diagram of optimal torque control MPPT method.

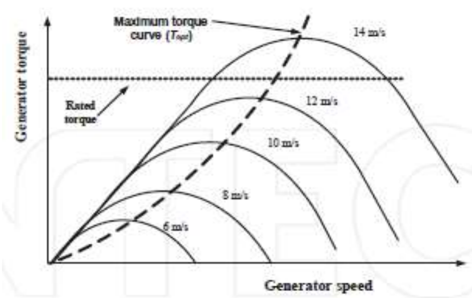

Fig 6. Wind turbine characteristic for maximum power extraction

D. Load angle control

The load angle control can be explained by analyzing the transfer of active and reactive power between two sources connected by an inductive reactance as shown in Figure 7. The active power, P, and reactive power, Q_s, transferred from the sending-end to the receiving-end can be calculated from the following equation

$$P_s = \frac{V_s V_R}{X_{gen}} \sin\delta \quad (9)$$

$$Q_s = \frac{V_s^2}{X_{gen}} - \frac{V_s V_R}{X_{gen}} \quad (10)$$

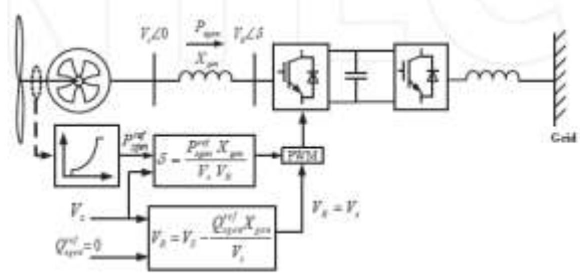

Fig 7. Load angle control of the generator-side converter

E. Load angle control of the generator-side converter

The operation of the generator and the power transferred to the dc-link are controlled by adjusting the magnitude and angle of the voltage at the ac terminals of the generator-side converter. This can be achieved using the load angle control technique where the internal voltage of the generator is the sending source *($V_s\angle 0$)*, and the generator-side converter is the receiving source *($V_R\angle\delta$)*. The inductive reactance between these two sources is the synchronous reactance of the generator, X_{gen}, as shown in Figure 7.

If it is assumed that the load angle δ is small, then sin $\delta \approx \delta$ and cos $\delta \approx 1$, Then the voltage magnitude, V_R, and angle magnitude, δ, required at the terminals of the generator-side converter are calculated using Equations (7) and (8) as shown [26]:

$$\delta = \frac{P_{Sgen}^{ref} X_{gen}}{V_s V_R} \qquad (11)$$

$$V_R = V_s - \frac{Q_{Sgen}^{ref} X_{gen}}{V_s} \qquad (12)$$

Where P_{Sgen}^{ref} is the reference value of the active power that needs to be transferred from the generator to the dc-link, and Q_{Sgen}^{ref} is the reference value for the reactive power. The reference value P_{Sgen}^{ref} is obtained from the characteristic curve of the machine for maximum power extraction for a given generator speed, ω_r. As the generator has permanent magnets, it does not require magnetizing current through the stator, thus the reactive power reference value can be set to zero, Q_{Sgen}^{ref} = 0 (i.e. V_S and V_R are equal in magnitude). The implementation of this load angle control scheme is illustrated in Figure 7. The major advantage of the load angle control is its simplicity. However, as the dynamics of the generator are not considered it may not be very effective in controlling the generator during transient operation [18].

F. Load angle control for the grid-side converter

The objective of the grid-side converter controller is to maintain the dc-link voltage at the reference value by exporting active power to the grid. In addition, the controller is designed to enable the exchange of reactive power between the converter and the grid as required by the application specifications. Also, the load angle control is a widely used grid side converter control method, where the grid-side converter is the sending source *($V_S\angle\delta$)*, and the grid is the receiving source *($V_R\angle 0$)*. As known, the grid voltage is selected as the reference; hence, the phase angle δ is positive. The reactance X_{grid} is the inductor coupling between these two sources [26]. The reference value for the active power, $P_{S\,grid}^{ref}$, that needs to be transmitted to the grid can be determined by examining the dc-link dynamics with the aid of Figure 8.

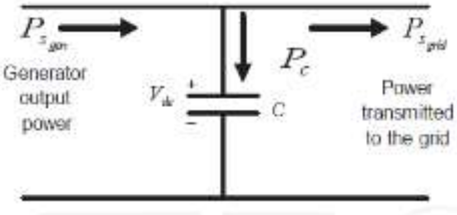

Fig 8. Power flow in the dc-link

This figure illustrates the power balance at the dc-link [26] as shown in the following equation:

$$P_c = P_{Sgen} - P_{Sgrid} \qquad (13)$$

where P_c is the power across the dc-link capacitor, *C*, P_{Sgen} is the active power output of the generator (and transmitted to the dc-link), and P_{Sgrid} is the active power transmitted from the dc-link to the grid.

The dc-link voltage V_{dc} can be expressed in terms of the generator output power, P_{Sgen}, and the power transmitted to the grid, P_{Sgen}, as shown in the following [26]:

$$V_{dc} = \sqrt{\frac{2}{C}\int\left(P_{Sgen} - P_{Sgrid}\right)dt} \qquad (14)$$

Equation (12) calculates the actual value of V_{dc}. The reference value of the active power, P_{Sgrid}^{ref}, to be transmitted to the grid is calculated by comparing the actual dc-link voltage, V_{dc}, with the desired dc-link voltage reference, $V_{dc\text{-}ref}$. The error between these two signals is processed by a PI-controller, whose output provides the reference active power P_{Sgrid}^{ref}, as shown in Figure 9. Figure 10 illustrates the implementation of the load angle control scheme for the grid-side converter with unity power factor [21].

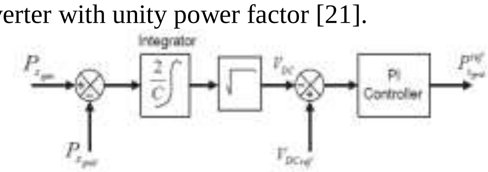

Fig 9. Calculation of active power reference, P_{Sgrid}^{ref}

IV.CO-SIMULATION (PSIM/MATLAB) PROGRAM FOR INTERCONNECTION WIND ENERGY SYSTEM WITH ELECTRIC UTILITY

In this study, the WECS is designed as PMSG connected to the grid via a back-to-back PWMVSC as shown in Figure 10. MPPT control algorithm has been introduced using FLC to regulate the rotational speed to force the PMSG to work around its maximum power point in speeds below rated speeds and to produce the rated power in wind speed higher than the rated wind speed of the WT. Indirect vector-controlled PMSG system has been used for this purpose. The input to FLC is two real time measurements which are the change of output power and rotational speed between two consequent iterations (Δp, and $\Delta_{\omega m}$). The output from FLC is the required change in the rotational speed $\Delta_{\omega m\text{-}new}$*. The detailed logic behind the new proposed technique is explained in details in the following sections. Two effective computer simulation software packages (PSIM and Simulink) have been used to carry out the simulation effectively where PSIM contains the power circuit of the WECS and Matlab/Simulink contains the control circuit of the system. The idea behind using these two different software packages is the effective tools provided with PSIM for power circuit and the effective tools in Simulink for control circuit and FLC.

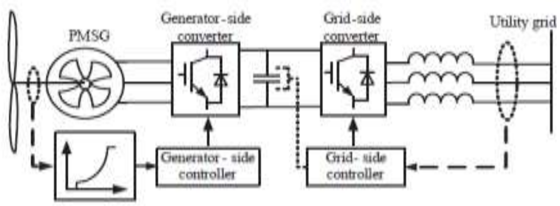

Fig 10. Schematic diagram of the overall system

A. Wind energy conversion system description

Figure 11 shows a co-simulation (PSIM/Simulink) program for interconnecting WECS to electric utility. The PSIM program contains the power circuit of the WECS and Matlab/Simulink program contains the control of this system. The interconnection between PSIM and Matlab/Simulink has been done via the SimCoupler block. The basic topology of the power circuit which has PMSG driven wind turbine connected to the utility grid through the ac-dc-ac conversion system is shown in Figure 10. The PMSG is connected to the grid through back– to-back bidirectional PWM voltage source converters VSC. The generator side converter is used as a rectifier, while the grid side converter is used as an inverter. The generator side converter is connected to the grid side converter through dc-link capacitor. The control of the overall system has been done through the generator side converter and the grid side converter. MPPT algorithm has been achieved through controlling the generator side converter using FLC. The grid-side converter controller maintains the dc-link voltage at the desired value by exporting active power to the grid and it controls the reactive power exchange with the grid.

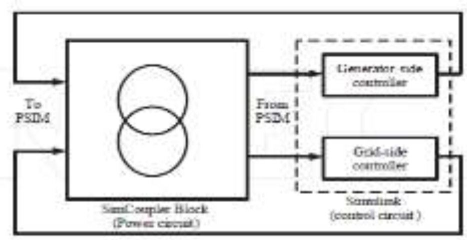

Fig 11 . Co-simulation block of wind energy system interfaced to electric utility

B. Simulation results

A co-simulation (PSIM/Simulink) program has been used where PSIM contains the power circuit of the WECS and Matlab/Simulink has the whole control system as described before. The model of WECS in PSIM contains the WT connected to the utility grid through back–to-back bidirectional PWM converter. The control of whole system in Simulink contains the generator side controller and the grid side controller. The wind turbine characteristics and the parameters of the PMSG are listed in Appendix. The generator can be directly controlled by the generator side controller to track the maximum power available from the WT. The wind speed is variable and changes from 7 m/s to 13 m/s as input to WT. To extract maximum power at variable wind speed, the turbine should always operate at λ_{opt}. This occurs by controlling the rotational speed of the WT. So, it always operates at the optimum rotational speed. ω_{opt} changes from a certain wind speed to another. The fuzzy logic controller is used to search the optimum rotational speed which tracks the maximum power point at variable wind speeds. Figure 12 (a) shows the variation of the wind speed which varies randomly from 7 m/s to13 m/s. On the other hand, Figure 12 (b) shows the variation of the actual and reference rotational speed as a result of the wind speed variation. At a certain wind speed, the actual and reference rotational speed have been estimated i.e. the WT always operates at the optimum rotational speed which is found using FLC; hence, the power extraction from wind is maximum at variable Maximum Power Extraction from Utility-Interfaced Wind Turbines wind speed. It is seen that according to the wind speed variation the generator speed varies and that its output power is produced corresponding to the wind speed variation. The fuzzy logic controller works well and it gives the good tracking performance for the maximum output power point. The fuzzy logic controller makes WT always operates at the optimum rotational speed. On the other hand, the grid-side controller maintains the dc-link voltage at the desired value, 600v, as shown in Fig 12 (c). The dc-link voltage is regulated by exporting active power to the grid as shown in Fig 12 (d). The reactive power transmitted to the grid is shown in Fig 12 (e).

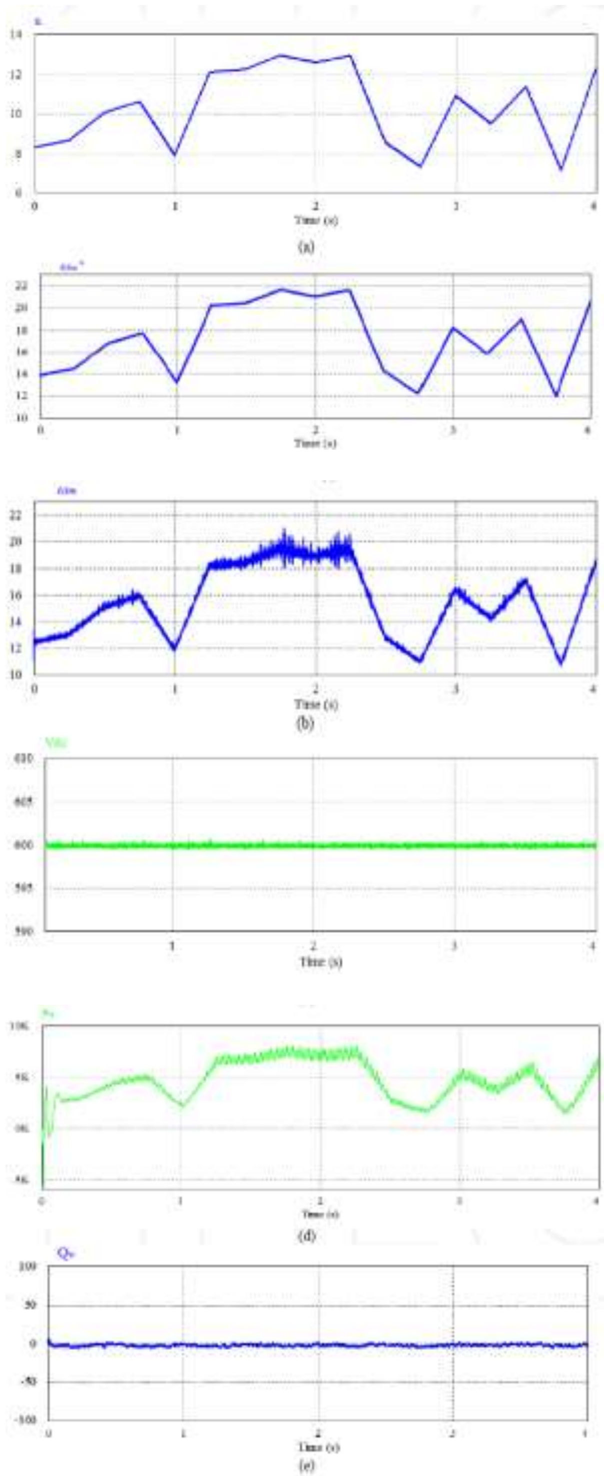

Fig 12. Different simulation waveforms: (a) Wind speed variation (7-13) m/s. (b) Actual and reference rotational speed (rad/s). (c) dc-link voltage (v). (d) Active power (watt). (e) Reactive power (Var).

V. CONCLUSION

Wind energy conversion system has high priority among the various renewable energy systems. Maximum power extraction from wind energy system became an important research topic due to the increase in output energy by using this technique. Wind speed sensorless MPPT control has been a very active area of research. In this study, a concise review of MPPT control methods has been presented for controlling WECS. Wind power generation has grown at a high rate in the past decade and will continue with power electronic technology advanced. A co-simulation (PSIM/Simulink) program has been proposed for WECS where PSIM contains the power circuit of the WECS and Matlab/Simulink has the control circuit of the system. The WT is connected to the grid via back–to-back PWM-VSC. The generator side controller and the grid side controller have been done in Simulink. The main function of the generator side controller is to track the maximum power from wind through controlling the rotational speed of the turbine using fuzzy logic controller. The fuzzy logic algorithm for the maximum output power of the grid-connected wind power generation system using a PMSG has been proposed and implemented above. The PMSG was controlled in indirect-vector field oriented control method and its speed reference was determined using fuzzy logic controller. The grid-side converter controls the dc-link voltage at a desired value, 600V, for the proposed system. Active and reactive power control has been achieved by controlling q-axis and d-axis grid current components respectively. The d-axis grid current is controlled to be zero for unity power factor and the q-axis grid current is controlled to deliver the power flowing from the dc-link to the grid. The simulation results prove the superiority of FLC and the whole control system.

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