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A SENSORLESS POWER SMOOTHING METHOD FOR A GRID-CONNECTED WIND ENERGY SYSTEM BASED ON FUZZY INTERFERENCE SYSTEM

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Abstract. *This paper proposes a control strategy to smooth the output power of a wind energy system using battery energy storage system (BESS). The proposed control consists of an optimal power extractor, a BESS controller and a grid side controller. The optimal power is obtained using fuzzy controller by setting the duty cycle of the boost converter. Based on the simulation result, the proposed control produces a good performance under high fluctuating wind speeds. The use of fuzzy controller can capture more power than the perturb & observe (P&O) method to wind speeds variation. The proposed control strategy can maintain stable power injection.*
Keywords: Wind turbine, Fuzzy controller, Permanent magnet synchronous generator (PMSG), Optimal power extraction

1. **Introduction.** Wind energy system has increased considerably during past few years and it is likely to rise in near future. Currently, variable speed wind turbine (VSWT) is widely used as wind generation technology because of its efficiency. Moreover, the VSWT has lower mechanical losses since it does not need gearboxes [1]. In order to increase the captured power, the wind turbine must operate at the maximum power point. This can be obtained if the generator works at its optimum speed. Therefore, a controller is required to track the optimum power point on a wind turbine that is highly dependent on wind speed characteristics.

Several methods have been developed to extract the optimal power from wind generation system. The use of mechanical sensors for wind speed is used in the tip speed ratio (TSR) method and optimum torque control for maximum power tracking. Optimal power is achieved when the wind turbine reaches the optimal TSR value. OTC method produces better performance than TSR [2]. The perturb & observe (P&O) method was developed for optimum power tracking because it is a simple method and easy to implement. However, the use of mechanical sensors caused to reduced system efficiency and increased system costs. In addition, the P&O method produced oscillations under steady state conditions and is highly dependent on the determination of step size [3,4]. To overcome the weakness of the P&O method, some researchers have developed fuzzy logic controller for optimal power tracking. The fuzzy controller is used to extract maximum power in wind turbines connected to the grid based on rotational speed and mechanical power [5]. However, the use of mechanical sensors for rotational speed measurement reduces the effectiveness of wind turbine systems. Fuzzy logic control is used to find maximum power through setting of the duty cycle of the DC-DC converter and it produces good performance [6,7].

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As the wind speed changes, the wind generation system will produce fluctuated power. A control system to stabilize the wind turbine output power using battery is developed through bidirectional converter and maximum power extraction performed by a simple method through switch mode rectifier setting. However, the use of switch mode rectifier increases the complexity of the controls because more switches are controlled [8]. The use of batteries to obtain constant power based on state of charged (SOC) of battery has developed, but does not consider maximum power extraction [9]. In this paper we will develop control strategies for wind energy systems equipped with batteries to maintain power as needed on the grid. In addition, the wind energy system is also equipped with fuzzy logic-based optimal power extraction without the use of mechanical sensors so that the system is more efficient and effective. The search for the optimal power point is based on the output power of the uncontrolled diode rectifier and the rectifier output voltage through the duty cycle boost converter setting. Meanwhile, to get the constant power is done through the BESS controller and grid side controller. In this paper, wind energy system modeling is given in Section 2, control system design is given in Section 3, and simulation result and conclusions are given in Section 4 and Section 5.

2. **Wind Energy System Modeling.** Figure 1 shows the configuration of the wind energy system connected to the grid. The system consists of a vertical wind turbine system with a PMSG connected to an uncontrolled diode rectifier that will convert the AC signal into a DC signal. The optimal power is obtained by controlling the duty cycle of the boost converter. The boost converter output is connected with the grid through the inverter which will convert the DC signal into AC. The control strategy on the proposed wind energy system consists of fuzzy controller, BESS controller and grid side controller. Fuzzy controller functions to extract optimum power through the duty cycle of boost converter arrangement based on the output voltage of rectifier and rectifier output power. The fuzzy controller optimizes the optimum power so that the wind energy system can generate maximum power on any wind changes. Fluctuating wind speed will produce a fluctuating optimum power as well so that a battery is required to store and supply power as required. BESS controller serves to control the charge and discharge the battery by using the controller PI to maintain the DC voltage. Grid side controller serves to control the inverter so that it obtained unity power factor at grid. The proposed control will be compared to the P&O method.

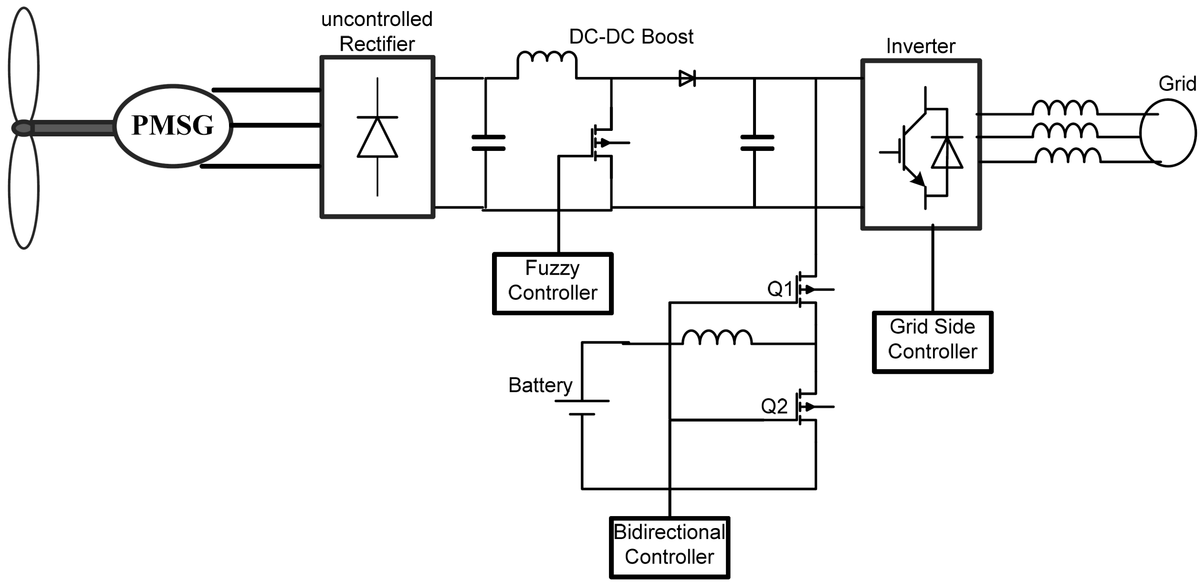


Figure 1. Block diagram of wind energy system

The mechanical power generated by the wind turbine can be expressed by

$$P_m = 0.5\pi\rho C_p(\lambda, \beta)R^2v^3 \tag{1}$$

in which ρ denotes air density (kg/m^3), C_p is power coefficient of turbine power conversion, R is turbine radius (m) and v is wind speed (m/s). C_p is a function of tip speed ratio (λ) and pitch angle (β) in degree. If β equals zero so C_p can be expressed by [10]

$$C_p = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \tag{2}$$

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

λ is comparison between angular speed of turbine (ω_r) and wind speed (v) that can be expressed by

$$\lambda = \frac{\omega_r R}{v} \tag{4}$$

If pitch angle equals zero, the optimal value (C_p) is 0.48 and λ is 8.1.

The proposed wind energy system used PMSG as a generator that converts mechanical data into three phase electrical energy. PMSG has a simple structure, high efficiency, better reliability, high performance and low maintenance. PMSG modeling using the dq axis equation can be expressed by

$$v_{ds} = -i_{ds} \cdot R_s + \omega_L \cdot L_q \cdot i_{qs} - p \cdot L_d \cdot i_{ds} \tag{5}$$

$$v_{qs} = -i_{qs} \cdot R_s - \omega_L \cdot L_d \cdot i_{ds} + \omega_L\lambda_r - p \cdot L_q \cdot i_{qs} \tag{6}$$

in which i_{ds} is the d axis stator current, i_{qs} is the q axis stator current, v_{ds} is the d axis stator voltage, v_{qs} is the d axis stator voltage, R_s is winding resistance (Ω), L_d is winding inductance on d axis (H), L_q is winding inductance on q axis (H), p is pole number, ω_L is rotation speed of PMSG (rad/s) and λ_r is rotor flux.

3. **Control System.** The control system works to get power smoothing to fluctuations in wind speed with maximum power extraction using fuzzy controller without mechanical sensors and BESS controller so the system becomes more efficient. Optimal power is obtained based on the current and output voltage of the rectifier. The control system in this paper can be divided into three: fuzzy controller, BESS controller and grid side controller.

3.1. **Fuzzy based optimal power extraction.** Based on the wind turbine characteristics curve, the maximum power point of the wind energy system can be achieved if $dp/d\omega$ is equal to 0. Based on the relationship between variables and chain rule, it can be determined by

$$\frac{dP_{dc}}{d\omega} = \frac{dP_{dc}}{dV_{dc}} \cdot \frac{dV_{dc}}{d\omega} = 0 \tag{7}$$

where P_{dc} is output power of rectifier and V_{dc} is the output voltage of the rectifier which can be expressed by

$$V_{dc} = \frac{3\sqrt{6}}{\pi}(E_g - I_g(R_s + jp\omega L_s)) \tag{8}$$

in which E_g denotes the electromotive power of PMSG and I_g is the PMSG phase current. In the PMSG, the resulting electromotive power is proportional to the output voltage of the rectifier. In this paper, optimal power extraction was designed without rotor speed and wind speed measurement so as to simplify the control design would be better using a straight line approach which can be expressed by

$$V_{dc} = K_r \cdot \omega \tag{9}$$

$$\frac{dV_{dc}}{d\omega} = K_r > 0 \tag{10}$$

Substituting Equation (6) to (9) we get:

$$\frac{dP_{dc}}{d\omega} <==> \frac{dP_{dc}}{dV_{dc}} = 0 \tag{11}$$

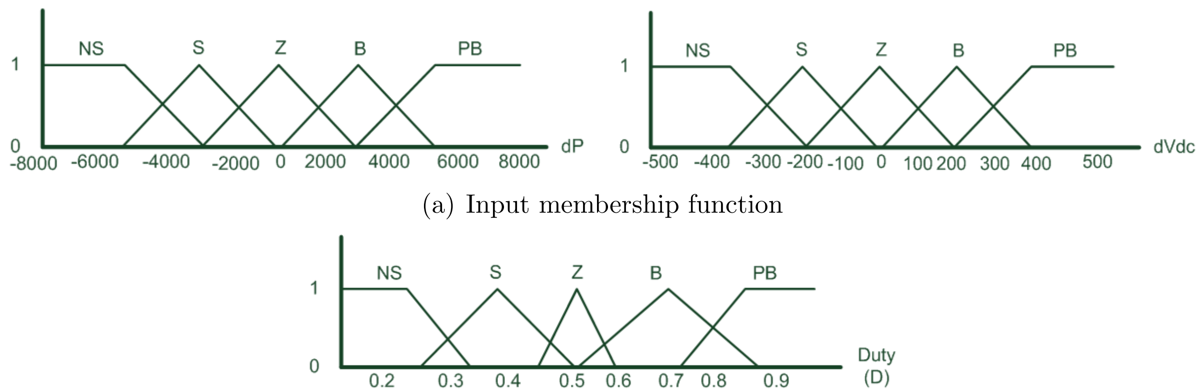
Based on Equation (10) optimum power points will be achieved if $\frac{dP_{dc}}{dV_{dc}}$ is 0 and the rotor speed change is proportional to the output voltage of the rectifier.

In this paper, the fuzzy controller has two inputs, i.e., dP and dV. dP is the difference between current and previous power, whereas dV is the difference between the current and previous rectifier output voltages, which can be expressed

$$dV = V(n) - V(n-1) \tag{12}$$

$$dP = P(n) - P(n-1) \tag{13}$$

Each fuzzy logic input, dP and dV, has five membership functions, as shown in Figure 2. Inference engine on fuzzy controller using max-min method and defuzzification process which will change duty cycle from the fuzzy value to numeric value, uses center of gravity method.



(a) Input membership function

(b) Output membership function

FIGURE 2. Membership function

3.2. **Battery charger controller.** The battery as an energy storage is connected to a DC-link voltage through a bidirectional buck boost converter, which consists of two switching components that work interchangeably. The control on the bidirectional converter aims to maintain the DC link voltage at a constant value against changes in wind speed. In addition, it will also maintain a power balance between the power generated by the wind turbine and the power required by the grid. The controller on the bidirectional converter uses a proportional integrator differentiator (PID) controller based on DC link voltage, DC link reference voltage and error. If the DC voltage is greater than the reference voltage, then the battery will be charged and contrarily if the DC voltage is lower than the reference voltage, then the battery will supply to the DC link to maintain the DC voltage link according to the reference. The PID controller used can be determined by

$$U(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \tag{14}$$

in which $U(t)$ is a control signal, K_p is a proportional gain, K_i is an integration gain, K_d is a differential gain and $e(t)$ is an error. The output from the PID controller will be through the pulse width modulation (PWM) generator to generate the duty cycle. The parameter values of PID controller in this study were $K_p = 400$, $K_i = 10$ and $K_d = 0.4$.

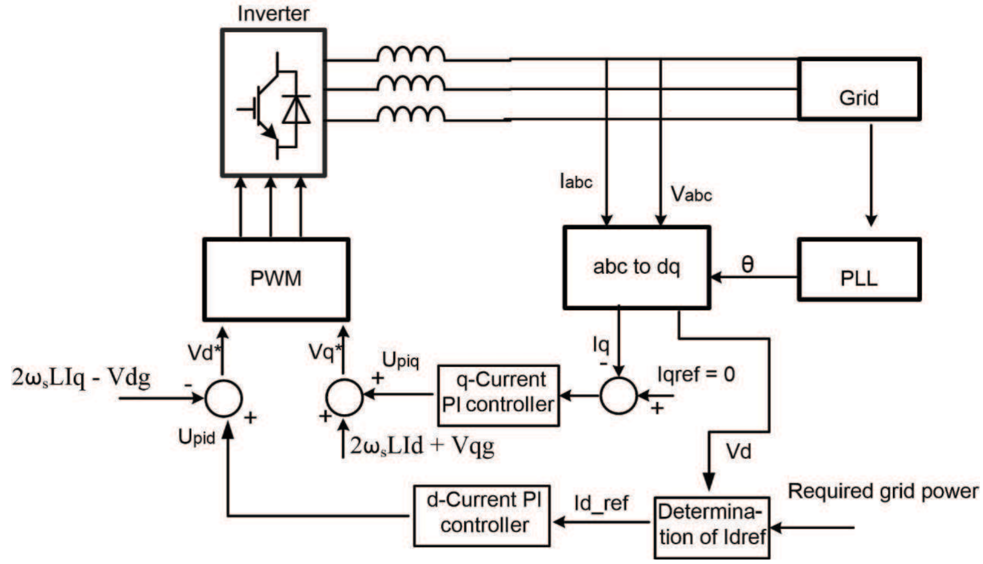


FIGURE 3. Grid side controller

3.3. **Grid side controller.** The grid side controller adjusts to the grid side converter (GSC) by controlling the dq axis currents and based on the power required by the grid [10]. The controller used in the current control is the PI controller. Figure 3 shows the GSC control consisting of two PI controllers for the d-axis and the q-axis currents, the PWM generator and the phase locked loop (PLL). Control of the d-axis current and q-axis current is done by using a PI controller where the d-axis reference current (i_{dref}) is determined by

$$i_{dref} = \frac{P_{ref}}{1.5v_{dg}} \tag{15}$$

where P_{ref} is reference power. To get unity power factor, the reference current of the q axis (i_{qref}) is set to zero. The output control system for controlling the d axis current (U_{pid}) and the q axis current (U_{piq}), can be expressed by [10]

$$v_d = U_{pid} - 2\omega_s Li_q + v_{dg} \tag{16}$$

$$v_q = U_{piq} + 2\omega_s Li_d + v_{qg} \tag{17}$$

The PI control system in Laplace transform is expressed by

$$U_{pi}(s) = K_p \left(1 + \frac{1}{Tis}\right) [I^*(s) - I(s)] \tag{18}$$

Ti corresponds to integrator constant and I^* is reference current in Laplace transform. By simplifying, the closed-loop transfer function of the current control systems can be expressed by

$$H(s) = \frac{I(s)}{I^*(s)} = \frac{\left(\frac{1}{R}\right) K_p \left(s + \frac{1}{Ti}\right)}{s\left(\left(\frac{L}{R}\right)s + 1\right) + \left(\frac{1}{R}\right) K_p \left(s + \frac{1}{Ti}\right)} \tag{19}$$

4. **Simulation Result.** The PMSG and wind turbine that is used in simulation is small scale wind turbine and their parameters are listed in Table 1. The optimal control performance with fuzzy extractor maximum power has been compared with optimal control using perturb & observe method. The simulation is done by giving two conditions: wind speed change – constant power requirement and wind speed change – power requirement change.

TABLE 1. PMSG and wind turbine simulation parameters

Items	Specification
Power rating	8.5 kW
Stator resistance	0.425 Ω
Stator inductance	0.0082 H
Pole pairs	10
PMSG flux	0.433 Wb
Turbine inertia	0.01197 kgm^2
Maximum C_p	0.48

4.1. **Case 1: wind speed change – constant power requirement.** The proposed control strategy for wind turbine system is tested under rapid changing of wind speed conditions. The wind speed varies between 5.5 m/s up to 9.5 m/s as shown in Figure 4 and the power requirement on the grid is constant at 4000 watts. The performance of the fuzzy controller to extract the optimum power is compared to the P&O method is shown by Figure 5. Fuzzy controllers and P&O methods can extract optimum power following wind speed changes, but the P&O method produces greater fluctuations. Besides, the use of fuzzy logic produces more power than the P&O method. At wind speeds of 8 m/s, power extraction with fuzzy logic can capture power of 5400 watts; however, the P&O method is only 5000 watts. At wind speeds between 8.5 m/s up to 9.5 m/s, fuzzy logic can capture power about 6000 watts and the P&O method is only 5200 watts.

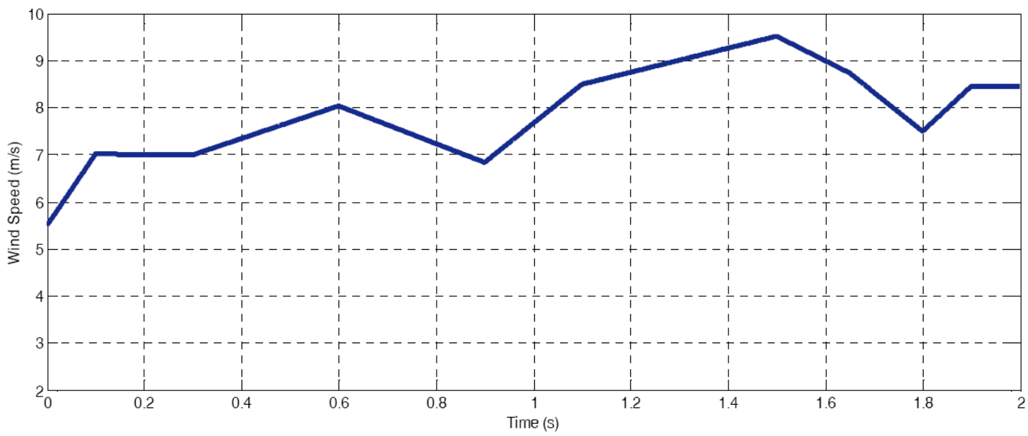


FIGURE 4. Wind speed

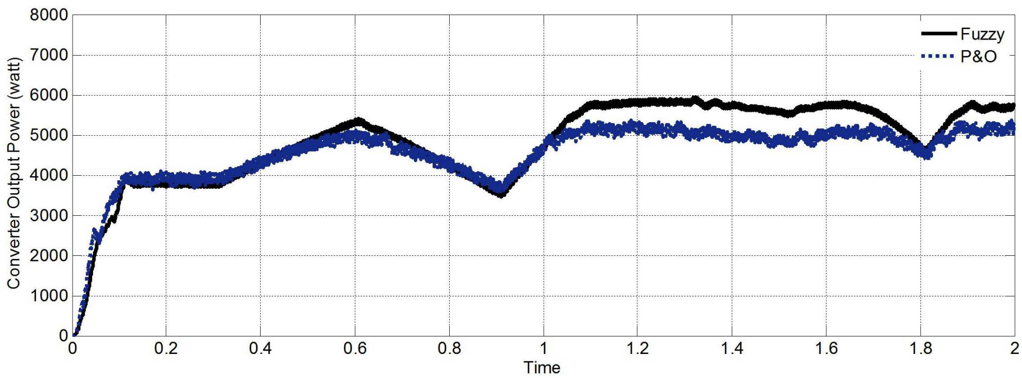
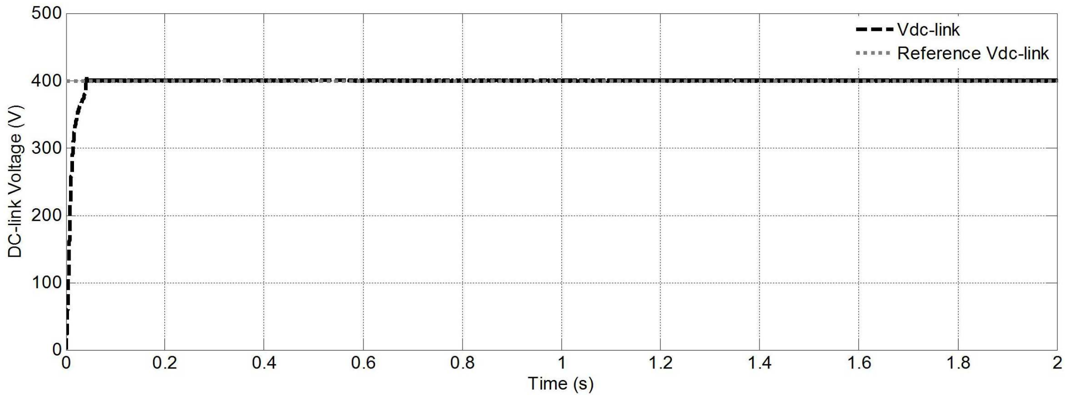
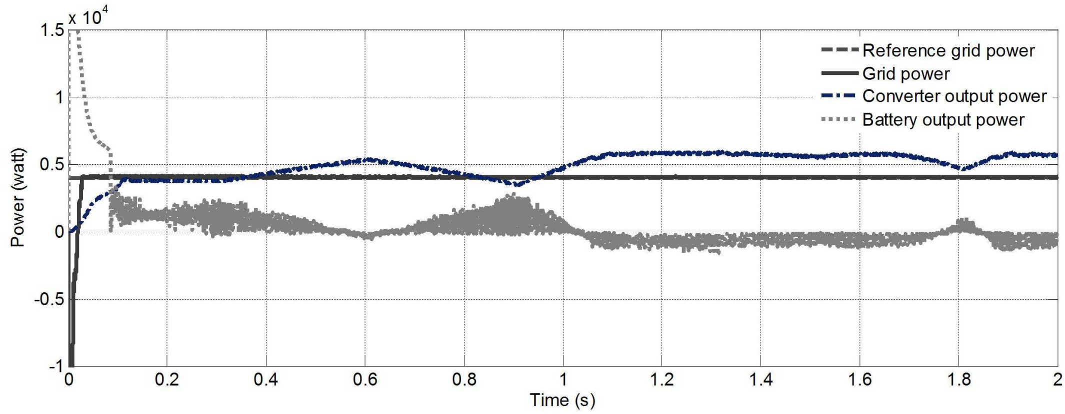


FIGURE 5. Output power of converter with optimum power extraction

The use of BESS can retain grid power as desired, although wind speed and converter output power vary. BESS will charge and discharge through BESS controller settings so that the DC link voltage can be maintained constant at 400 V, as shown in Figure 6(a). Figure 6(b) shows reference grid power, grid power, output power of converter and battery output power by using a fuzzy controller to extract optimum power. The grid power is kept constant at 4000 watts. With varying wind speed, converter output power will vary as well. At 0 to 0.4 s converter power is lower than that of the required grid power and then BESS will discharge to supply the grid. Whereas in 1 s to 2 s, converter



(a) DC link voltage



(b) Grid power, output power of converter and battery output power

Figure 6. Wind turbine system performance with fuzzy controller to extract optimum power to wind speed variation

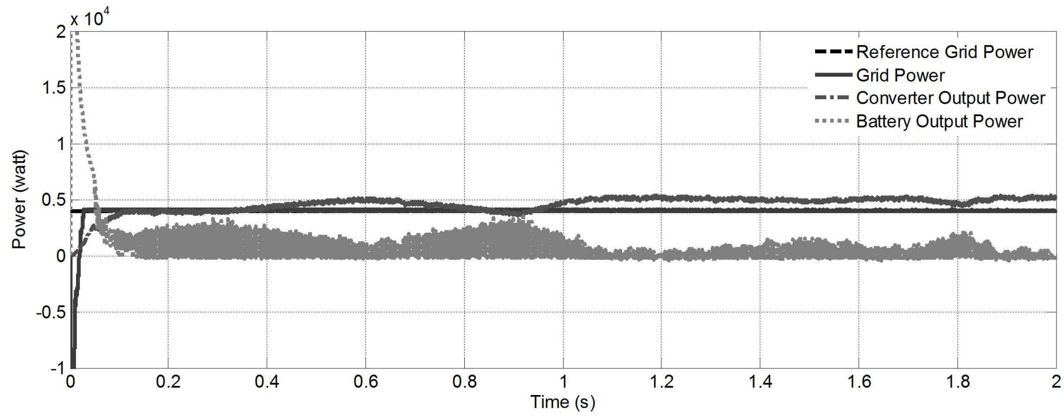
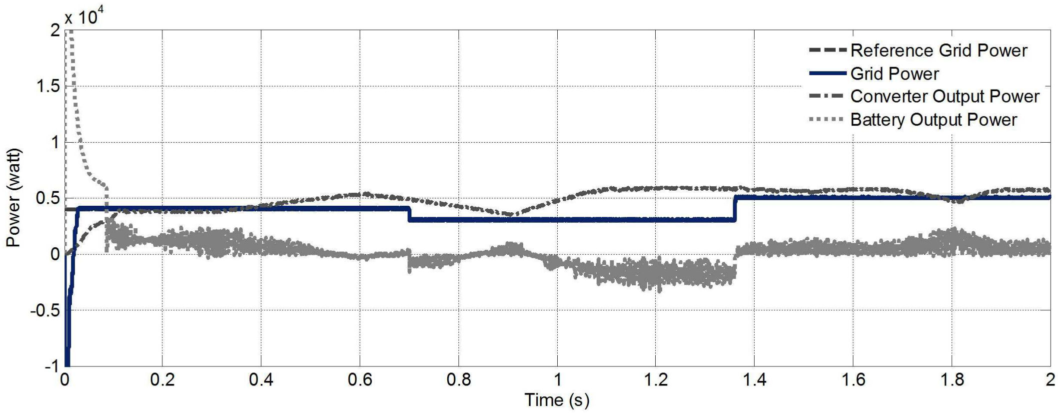
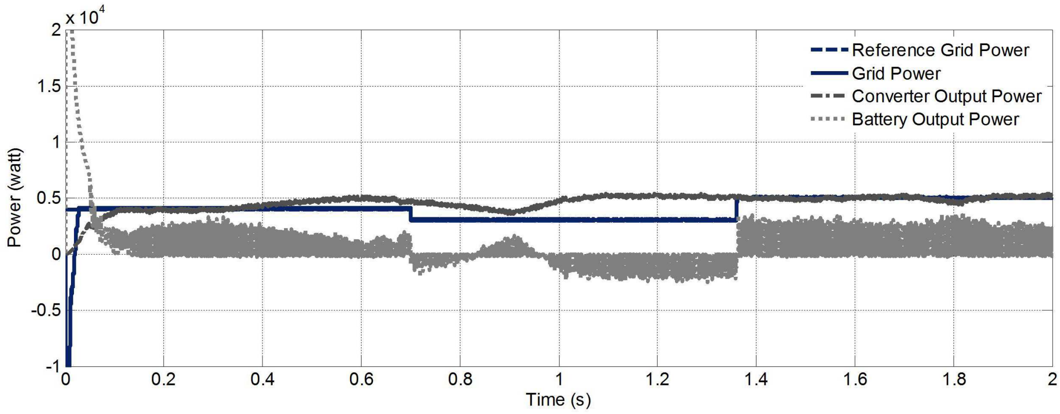


Figure 7. Wind turbine system performance with P&O method to extract optimum power to wind speed variation



(a) Output power with fuzzy controller



(b) Output power with P&O method

FIGURE 8. The performance of wind turbine system to wind speed variation and grid power change

output power is greater than 4000 watts and then BESS will charge indicated by battery power with different polarity.

Figure 7 shows grid reference power, grid power, output power of converter and battery output power by using P&O method to extract optimum power. This method can also maintain grid power in accordance with the reference but battery output power fluctuations greater than the use of fuzzy controller.

4.2. **Case 2: wind speed change – power requirement change.** Figure 8 shows reference grid power, grid power achieved, converter output power and battery output power on wind turbine system to changes in wind speed and grid power. Testing is done by giving step power changes from 4000 watts to 3000 watts and raised to 5000 watts. Control strategy using fuzzy logic and the P&O method can produce grid power according to reference through charge and discharge battery settings. However the P&O method produces considerable battery power fluctuations that can affect life time of battery.

5. **Conclusions.** A control strategy for wind generation system has been presented in this paper. To smooth the output power, the BESS is used. The proposed control consists of a fuzzy controller to extract optimal power through setting duty cycle on boost converter, BESS controller and grid side controller. Based on simulation result, the use of the fuzzy controller provides smoother power than that of the P&O method. The proposed control can produce power smoothing as required against wind speed variations and grid power changes. Future research will develop supervisory control of wind turbine by using BESS based on state of charge battery condition.

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