ENERGY MANAGEMENT OF WIND POWER SUPPLY SYSTEM WITH BATTERY STORAGE

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Abstract

Wind power supply system is an effective, environmentally friendly power source for household and other applications. In this paper, optimal energy management for a stand-alone wind power supply system with battery storage system is proposed to sufficiently explore wind energy for customers at demand side. The management of power flow aims to optimal energy supply subject to a number of constraints, such as power balance, wind power output and battery capacity. Wind turbine is connected with permanent magnet synchronous generator (PMSG), power electronic devices and battery bank. Battery bank is used to store the surplus of energy when the load demand is low and discharges again the stored energy to the load when wind power is not sufficient to supply the load. The proposed system can meet the load for every hour of the days without interruption. In this research, the average daily load requirement of weekend is chosen because it is the highest in energy consumption. The simulation results show that the management of the system is satisfied between available wind power and load demand.

Keyword: wind Power, battery storage, permanent magnet synchronous generator (PMSG), power electronic device, wind turbine.

1. INTRODUCTION

The renewable energy sources are one of the biggest concerns of the energy world. High prices of oil and global warming make the fossil fuels less and less attractive solutions. Wind power is a very important renewable energy source. It is free and not polluter unlike the traditional fossil energy sources. Renewable energy sources including wind power offer a feasible solution to distributed power generation for isolated communities where utility grids are not available. In such cases, stand-alone wind energy systems can be considered as an effective way to provide continuous power to electrical loads. One of the most promising applications of renewable energy generation lies in the development of power supply systems for remote communities that lack an economically feasible means of connecting to the main electrical grid. For isolated settlements located far from a utility grid, one practical approach to self-sufficient power generation involves using a wind turbine with battery storage to create a stand-alone system.

In this paper, the stand-alone wind power supply system with battery energy storage system is chosen by using the load demand. This paper proposes the variable speed stand-alone wind power supply system that includes Permanent Magnet Synchronous Generator, three phase diode rectifier, DC-DC boost converter, battery energy storage system, and voltage source inverter. The power conversion model for each system component is designed for supplying stable load voltage under wind speed variation and load changes. Control of the DC-DC bidirectional buck-boost converter, which is connected between batteries bank and DC-link voltage, is used to maintain the DC-link voltage at a constant value. It is also used to make the battery bank stores the surplus of wind energy and supplies this energy to the load during the wind power shortage. The battery bank is connected to DC-link through a bidirectional buck-boost converter for its charge mode and discharge mode operation.

Generally, when a power system is designed, the capacity of the resources within the system should be large enough to maintain the reliability level. Modeling a renewable energy system is quite different from modeling a conventional system. A stand-alone wind power supply system with battery energy storage system has been suggested to meet the demand reliably. This problem has been solved by applying MATLAB/SIMULINK and Microsoft Office Excel.

2. WIND POWER SUPPLY SYSTEM WITH BATTERY STORAGE SYSTEM

The most important technical information for a specific wind turbine is the power curve which shows the relationship between wind speed and the electrical power output of the generator. According to the power curve, there are three types of wind speeds, cut-in wind speed, rated wind speed, and cut-out wind speed. The cut-in wind speed is the minimum wind speed needed to generate net power. The generator is delivering as much power as it is designed for when the wind speed reach at the rated speed. At cut-out wind speed, the machine must be shut down.[1]

The wind turbine is connected with the permanent magnet synchronous generator to extract electrical energy from wind power. The power circuit topology of the proposed variable speed stand-alone wind energy supply system is shown in Figure 1. The system consists of wind turbine, permanent magnet synchronous generator (PMSG), which is directly driven by the wind turbine without using a gearbox, a single switch three phase mode rectifier which consists of a three phase diode bridge rectifier and DC-DC boost converter, DC-DC bidirectional buck-boost converter, and battery bank. A three phase voltage source inverter is connected to the load through LC filter.

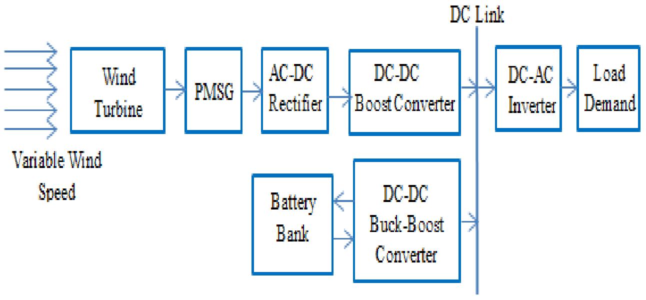


Figure1 Schematic diagram of the proposed system

2.1. Wind Turbine Model

The mechanical power captured from wind turbine is governed by the following equation:

$$P_m = 0.5\,\rho A C_p V_w^{\,3} \tag{1}$$

Where P_m is the mechanical output power of the wind turbine (Watt), ρ is the Air density (Kg/m^3), A is the swept area (m^2), C_p is the power coefficient of the wind turbine and V_w is the wind speed (m/s). The efficiency of a wind turbine includes the loss in the mechanical transmission, electrical generation, converter loss, etc, whereas the power coefficient is the efficiency of converting the power in the wind into mechanical energy in the rotor shaft. The power coefficient is usually given as a function of the tip speed ratio λ and the blade pitch angle β. If β is equal zero, in this case C_p is only function in λ, and λ is function of rotor mechanical speed, rotor radius of blade and wind speed as indicated in [2].

$$C_{p(\lambda)} = [(60.04\text{-}4.69\lambda)/\lambda]e^{[(\text{-}21+0.735\lambda)/\lambda]} + [0.0068\lambda/(1\text{-}0.035\lambda)] \tag{2}$$

$$\lambda = \omega_r R/V_w \tag{3}$$

Where ω_r is the rotational speed (rad/s) and R is the radius of blade (m). Maximum power from wind turbine can be extracted when the turbine operate at maximum C_p ($C_{p\text{-}opt}$). The optimum value of C_p is about 0.48 for λ equal 8.1 by assuming β is equal to zero degree. Therefore, it is necessary to adjust the rotor speed at optimum value of tip speed ratio (λ_{opt}) with wind speed variation to extract maximum power from wind turbine.[3]

2.2. Wind Turbine Generator

The function of an electrical generator is providing a mean for energy conversion between the mechanical torque from the wind rotor turbine, as the prime mover, and the local load or the electric grid. Different types of generators can be used with wind turbine systems. Both induction and synchronous generators can be used for wind turbine systems. The PMSG differs from the Induction Generator in that the magnetization is provided by a Permanent Magnet Pole System on the rotor, instead of taking excitation current from the armature winding terminals, as it is the case with the Induction Generator. The advantages of PM machines over electrically excited machines are that they have higher efficiency and energy yield. They do not need additional power supply for the magnet field excitation. Due to the absence of the field winding and mechanical components such as slip rings, it has smaller losses and higher reliability.[4]

The mathematical model of the PMSG in the synchronous reference frame (in the state equation form) is given by,

$$d_{i_d}/d_t = v_d/L_{ds} - (r_s/L_{ds})i_d + (L_{qs}/L_{ds})\omega_e \mathrm{i}_q \qquad (4)$$

$$d_{i_q}/d_t = (1/L_{qs})v_q - (r_s/L_{qs})i_q - (L_{ds}/L_{qs})\omega_e i_d - (\psi_f \omega_e/L_{qs}) \qquad (5)$$

$$T_e = 1.5p(L_{ds} - L_{qs})i_d i_q + i_q \psi_f \qquad (6)$$

Where, L_d, L_q are d and q axis inductances, R is stator winding resistance, i_d, i_q are d and q axis currents, v_q, v_d are d and q axis voltage, ω_r is angular velocity of rotor, λ is amplitude of rotor induced flux, p is pole pair number, and T_e is electromagnetic torque. Table I show the parameters of wind turbine and permanent magnet synchronous generator (PMSG). These parameters are applied to the simulation model of the proposed system.

Parameters	**Rating**
Rated wind speed	10.5 m/sec
Cut-in wind speed m/sec	5m/sec
Cut-out wind speed	25 m/sec
Blade diameter	10 m
Power coefficient	0.4
Swept area	78.5 m^2
Turbine rated speed	187 rpm
Rated power	18 kW
frequency	50 Hz
Pole pairs	16
R_s	0.056Ω
L_s	0.0011 mH

Table 1. Parameters of Wind Turbine and Generator

3. GENERATOR SIDE CONVERTER CONTROL

The generator side converter (switch mode rectifier) is used to extract maximum power from available wind turbine power. The generator side converter contains three phase diode rectifier and DC- DC boost converter.

3.1. Diode Rectifier

A rectifier is an electrical device that converts alternating current (AC), to direct current (DC), and this process is known as rectification. The three phase full-wave bridge rectifier is one of the most important circuits in high power applications. The rectifier can be connected directly to the three phase source. The average output voltage of the rectifier is

$$V_{dc} = \left(3\sqrt{2}/\pi\right)V_{LL} \qquad (7)$$

Where V_{dc} is DC or average output voltage and V_{LL} is AC line voltage. Filter capacitor to eliminate the output voltage ripples of the rectifier is

$$C_1 = 1/f_r R\, R_f \qquad (8)$$

3.2. DC-DC Boost Converter

The input to this converter is an unregulated DC voltage which can be obtained by rectifying an AC voltage source. This unregulated voltage will fluctuate due to changes in the line due to the fluctuation of wind speed. In order to control this unregulated DC voltage into a regulated DC output it is needed to use a DC-DC boost converter. The converter consists of an inductor L, an insulated gate bipolar transistor (IGBT), a diode, and a filter capacitor C. Filters made of capacitors are normally added to the output of the converter to reduce output voltage ripple .The circuit diagram of DC-DC boost converter is shown in Figure 2.

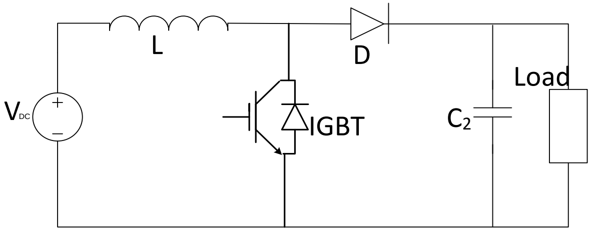


Figure 2Circuit diagram of DC-DC boost converter

The function of this circuit is that when the switch (IGBT) is closed, the input voltage is applied across the inductor, causing the current through the inductor to ramp up which then increases the energy stored in the inductor. Opening the switch will force the inductor current to flow through the diode and some of the energy stored in the inductor is transferred to the output filter capacitor and the output load [4]. The boost converter output voltage is obtained as

$$V_o = V_i/(1 - D) \qquad (9)$$

$$M_{VDC} = V_o/V_I = I_I/I_o = 1/(1\text{-}D) \tag{10}$$

$$L_1 = (2/27)(V_o/f_s I_{o\max}) \text{ ....} \tag{11}$$

$$C_2 = (D_{\max} V_o)/(f_s R_{L\min} V_{cpp}) \text{ ....} \tag{12}$$

Where, V_o is output voltage, V_i is input voltage, D is duty cycle, M_{VDC} is DC voltage transfer function, f_s (1 kHz) is switching frequency, L_1 is minimum inductance, I_{omax} is maximum output current. C_2 is minimum filter capacitance, and R_{Lmin} is minimum load resistance. The block diagram of the DC-DC boost controller is shown in Figure 3.

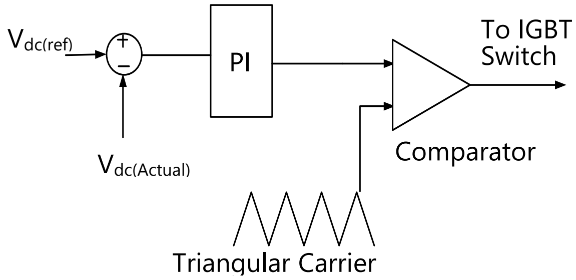


Figure 3Block diagram of typical DC-DC boost converter controller

The control of the DC-DC boost converter can extract maximum power from available wind power. In this paper Pulse Width Modulation (PWM) control method is used for DC-DC boost converter. In this method, the reference voltage, 566 V will be used to control the DC voltage at the rectifier DC side terminals. The reference voltage is compared with the actual voltage from the diode rectifier, and the error signal is fed to a PI controller. The output of PI controller is compared with carrier triangular wave by passing comparator to control the duty cycle of the IGBT switch.

3.3. DC-DC Bidirectional Converter Control

In stand-alone wind energy supply system, battery energy storage system is essential for storing the surplus energy when the load demand is low.[6] Then, the stored energy can be discharged again when the wind power is not high enough. The DC-DC bidirectional buck-boost PWM converter is used to perform the charge and discharge function to the battery bank. The design equations of the buck converter are as follows.

$$V_o = DV_1 \text{ ....} \tag{13}$$

$$M_{VDC} = V_o/V_I = I_I/I_o = D \text{ ....} \tag{14}$$

$$L_2 = R_{L\max}(1 - D_{\min})/2f_s \text{ ....} \tag{15}$$

$$C_3 = D_{\max}/(2f_s r_c) \text{ ....} \tag{16}$$

The equations of the boost converter are already described in the former section and the abbreviations are the same. The function of the controller is that the reference voltage ($V_{dc\text{-}ref}$) of the converter, 600V is compared with the actual dc voltage ($V_{dc\text{-}actual}$). The error signal is processed through the PI controller. The limiter limits the output of PI controller and compare with the high frequency saw tooth wave to generate the duty cycle of the switches Q_1 and Q_2. When the switch, Q_1 is on, the converter operates the buck function and charges to the battery bank. When the switch, Q2 is on, the converter operates as boost mode and discharges to the DC link. The block diagram of the DC-DC bidirectional converter controller is shown in Figure 4.

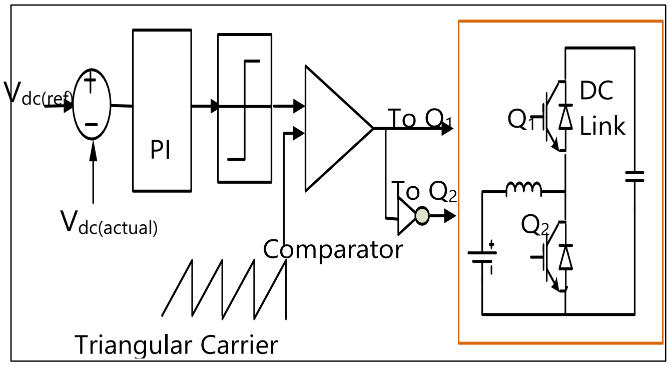


Figure 4Block diagram of typical DC-DC bidirectional buck-boost converter controller

3.4 Battery Bank

The battery bank stores the surplus of energy when the load demand is low, and discharges again the stored energy to the load when wind power is not sufficient to supply the load.[7] The battery bank voltage can be kept lower than the reference DC link voltage (600 V) via DC-DC bidirectional buck-boost PWM converter and hence less number of batteries needed to be connected in series. In the SIMULINK model, the battery bank voltage is kept at 300V for this system which can continuously supply 16 kW load nearly 6 hour when wind power is shortage. The depth of discharge (DOD) of the battery is considered at 80%. Therefore, twenty five numbers of batteries (each 12V, 300Ah rating) are needed to connect in series to get the battery bank voltage.

3.5. Load Side Inverter Control

The load side converter, a three phase voltage source inverter, is used as interface between DC link voltage and the load. Voltage source inverter is the most commonly used type. The input DC voltage may be from an independent source such as a battery or may be the output of a controlled rectifier. Therefore, the line-to-line rms voltage at the fundamental frequency, due to 120° phase displacement between phase voltages, can be written as,

$$V_{LL,\ (\text{line-line, rms})} = 0.612\, m_a V_d \quad (m_a \leq 1.0) \qquad (17)$$

It consists of six power IGBT switches. The switches are opened and closed periodically in the proper sequence to produce the desire output waveform. The output power of the inverter is

$$P_o = E^2 / 2R \qquad (18)$$

The RMS value of line voltage is

$$V_{L(RMS)} = E / \sqrt{2} \qquad (19)$$

Where, R is the resistance per phase and E is DC voltage.

The load side voltage source inverter control is responsible to regulate the voltage and frequency at the customer load. Load side voltage source inverter can generate unwanted high frequency harmonics based on the switching frequency. Pulse Width Modulation (PWM) control strategy is used to control the output load voltage during variation of wind speed. The filtered DC voltage from the DC link is applied to an IGBT two-level inverter. The voltage source inverter feeds the load through LC filter.[3,5]

4. ENERGY MANAGEMENT ALOGRITHM

The power management strategy should determine the power dispatch between the renewable energy sources, the energy storage devices and the load demand at charging station. When the energy generated by wind is greater than the energy required by the load, the energy surplus is stored in the batteries and the controller puts the battery in charge condition. When the battery SOC arrives the maximum value, the control system stops the charging process. When the wind energy is less than the energy required by the load, the energy deficit is covered by the storage and the controller puts the battery in the discharge condition. Therefore the power balance equality constraint is illustrated in Figure 5 for demand represented as P_L at any interval.

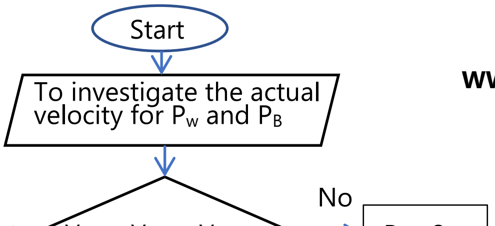


Figure 5Management Algorithm of System

5. RESULTS AND DISCUSSION

The proposed control strategy for the stand-alone variable speed wind energy supply system is MATLAB/SIMULINK under different operating conditions. Figure 6 shows the simulation block diagram for the system. And then simulation results are shown three case studies such as during the variation speed with constant load (16kW), during the variation load (16kW, 9kW, 11kW) with constant speed, during the variation speed with variation load.

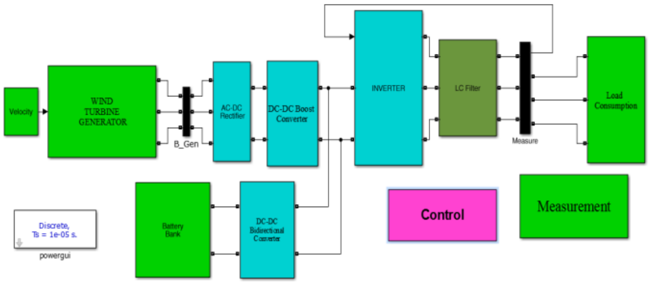
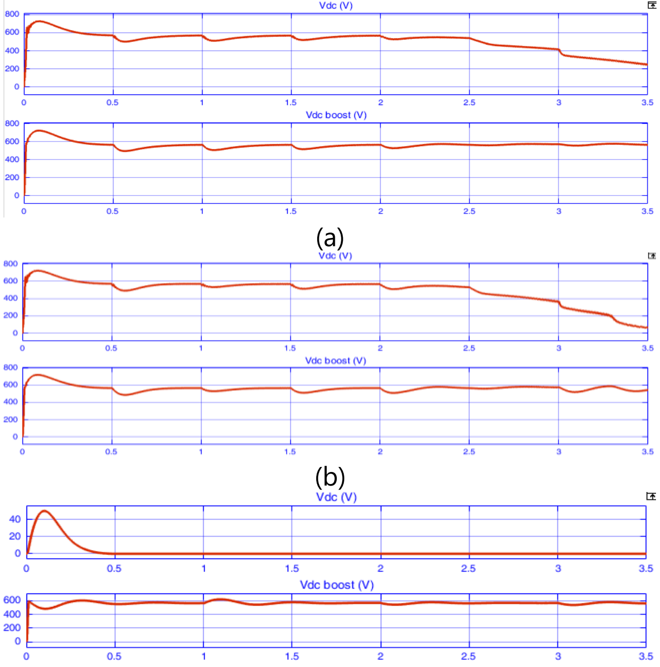


Figure 6Simulation Model of the Stand-alone Wind Power Supply System with Battery Storage

As the wind speed fluctuates, the output of generator is varied. When the wind speed is low, the generator output is also small. DC-DC converter can interface this problem. The results illustrate in below are at various wind speed conditions. Figure 7(a) and (b) show rectifier output voltage and boost converter output voltage of the stand-alone wind system during the variation speed with constant load and during the variation speed with variation load. This results almost same because of including wind power. At the variation load with zero speed condition, the stored energy from battery when wind power is shortaged. Therefore, after the rectifier output voltage is zero, DC link voltage can be obtained from battery storage.

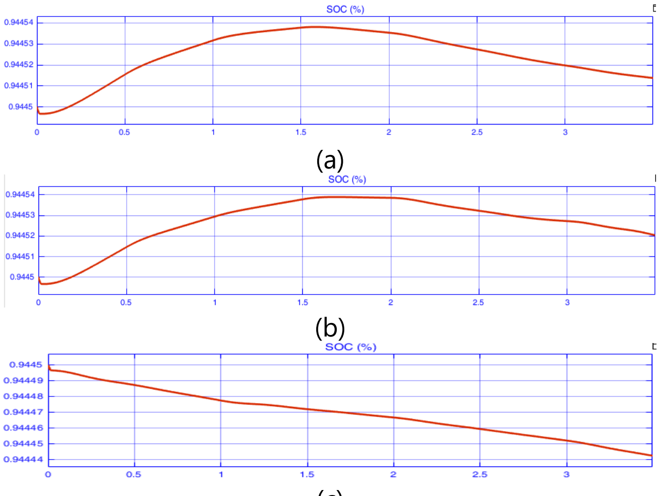


(a)

(b)

(c)

Figure7(a) Rectifier output voltage and boost converter output voltage of proposed system during the variation speed with constant load (b) during the variation speed with variation load (c) during the constant speed with variation load



(a)

(b)

(c)

Figure 8(a) Battery state of charge proposed system during the variation speed with constant load (b) during the variation speed with variation load (c) during the constant speed with variation load

Figure 8(a), (b) and (c) show battery state of charge proposed system at different conditions. The battery bank is charged through the converter when the load demand is lower than the generated power. The battery bank discharges the stored energy when the load demand is larger than the generated wind power. When the wind speed variation is between cut-in and rated speed, there is no extra energy to charge the battery as the available power is transferred to the load directly. Inverter output voltage and current of the proposed system can be seen in Figure9 and Figure 10 under different conditions. The load voltage is occurred under the wind speed variation between cut-in and rated speed. It can be seen that the load voltage is stable at 400 V under rated wind speed as shown in Figure 11.

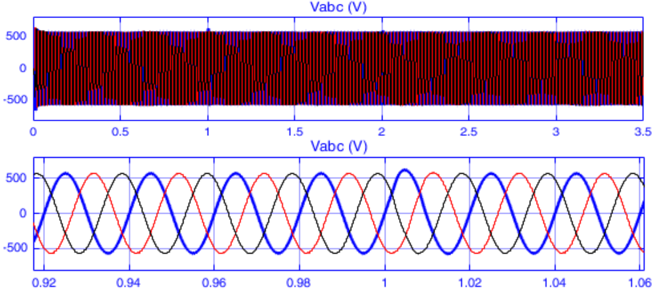
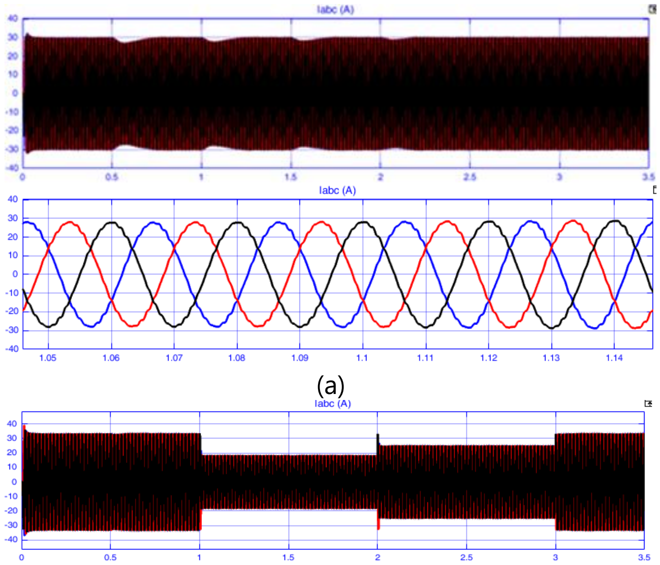
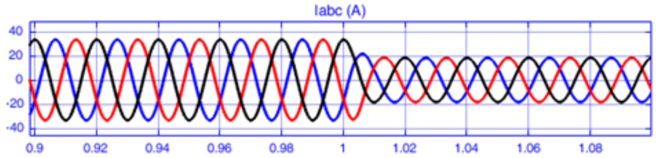


Figure 9Inverter output voltages throughout the full simulation time and Output voltages at simulation time 0.92 s to 1.06 s of the proposed system



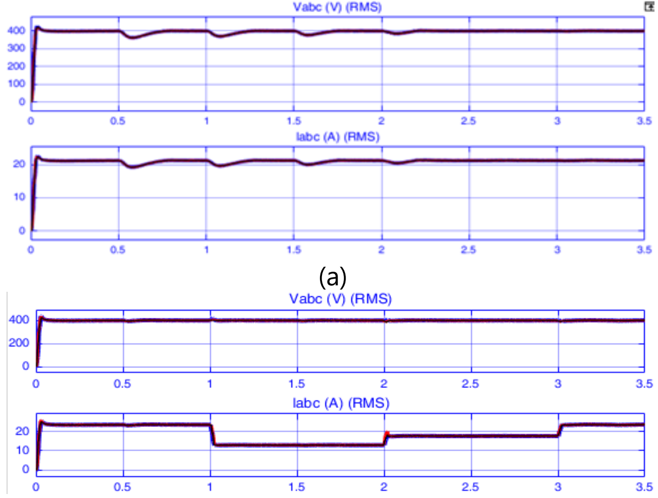
(a)



(b)

Figure10 Inverter output currents throughout the full simulation time and Output currents at simulation time from 0.9 s to 1.08 s of the proposed system (a) during the variation speed with constant load (b) during the variation speed with variation load

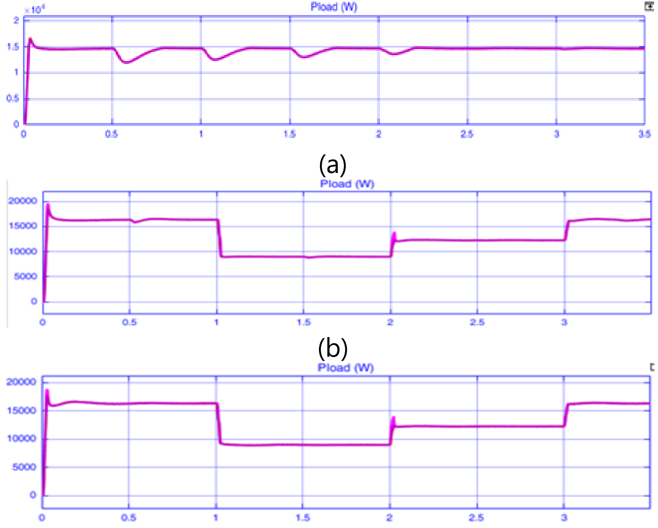
Figure 11 shows the load current of the system under different conditions. The load current varied depends on load variation. The first one condition differs from three conditions. The remained two conditions are equal.



(a)

(b)

Figure11Output line voltage and current of the proposed system (a) during the variation speed with constant load (b) during the constant speed with variation load



(a)

(b)

(c)

Figure 12 Load Power under different condition

According to simulation results, three case studies such as during the variation speed with constant load (16kW), during the variation load (16kW, 9kW, 11kW) with constant speed, during the variation speed with variation load are illustrated in figure12.

6. CONCLUSIONS

In this research, the energy management system and design consideration of wind power supply with battery storage system are mentioned. The wind speed variations can be sufficient to the monthly load power consumption. The wind power is not able sufficiently supplied when load demand exceeds the available power from the system for some hours in day. The battery bank stores the surplus of energy when the load demand is low and discharges again the stored energy to the load when wind power is not sufficient to supply the load. The management of the system is satisfied between available wind power and desired load demand. The further extensions are to implement conditions that the wind turbines should be added to the system in order to achieve enough energy for consumers. In order to achieve good DC link control in case of extra power produced while the battery is fully charged, a dump load such as electrolyzer should be added to the model.

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