CONTROL SCHEME OF STAND-ALONE WIND POWER SUPPLY SYSTEM WITH BATTERY ENERGY STORAGE SYSTEM

[1]TIN ZAR KHAING, [2]LWIN ZA KYIN

[1,2]Department of Electrical Power Engineering, Mandalay Technological University, Myanmar
E-mail: tinzakhaing.ep@gmail.com, lwinzakyin80@gmail.com

Abstract- Energy is the major input for overall economic development of the society. Among them, wind energy is the fastest growing renewable energy source. This paper proposes a control strategy for a variable speed stand-alone wind power supply system with battery energy storage system. Wind turbine is connected with permanent magnet synchronous generator (PMSG), switch mode rectifier, DC-DC bidirectional converter, battery bank, and voltage source inverter. Control of the switch mode rectifier is used to extract maximum power from available wind power. DC-DC bidirectional converter control is used to store the surplus energy and to discharge this energy when wind power is shortage. A voltage source inverter with Pulse Width Modulation (PWM) control is used to get the stable load side output voltage. The complete control scheme for wind power generating system has been applied using MATLAB/SIMULINK to supply the desire load.

Keywords- Battery bank, DC-DC Bidirectional Converter, Diode Rectifier, Permanent Magnet Synchronous Generator, Voltage Source Inverter

I. INTRODUCTION

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. For isolated places located far from a utility grid, one practical approach to self-sufficient power generation involves using a wind turbine with battery energy storage system [1]. Normally, there are two operating modes of wind turbine generators system such as fixed speed and variable speed operating modes. Variable speed wind energy systems have several advantages compared with fixed speed wind energy systems such as yielding maximum power output, developing low amount of mechanical stress, improving efficiency and power quality [2]. As wind speed is not constant, generator output is fluctuated. In order to achieve the stable power at the load side under the condition that the generator output power is variable, it is necessary to use a controller to get the stable output produced by the wind turbine generator. The reliability of the variable speed wind energy systems can be improved significantly by using a permanent magnet synchronous generator (PMSG). The horizontal axis, three blade wind turbine is directly connected with PMSG. The output of PMSG flows through three phase diode rectifier, DC-DC boost converter, DC-DC bidirectional converter, and voltage source inverter to the load. The AC-DC rectifier is a full bridge circuit to convert AC voltage to DC voltage. As the available wind speed is not constant, the boost circuit is employed to extract maximum power from available wind power. The DC-DC bidirectional converter is used to stabilize the voltage of DC link. Pulse Width Modulation (PWM) control is chosen to implement the DC-AC inverter. In the stand-alone wind energy systems, where there is no grid, the output voltages should be controlled in terms of amplitude and frequency [2].

II. STAND-ALONE WIND POWER SUPPLY 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 [3].

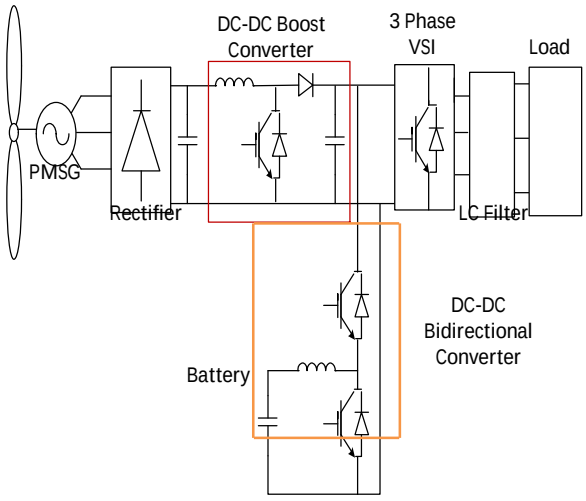


Fig. 1. Schematic diagram of the proposed system

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 Fig. 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.

A. Wind Turbine Model

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

$$P_m = 0.5\,\rho A C_p V_w^3 \quad (1)$$

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, where as 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).

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

$$\lambda = \omega_r R / V_w \quad (3)$$

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 [2].

B. 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 [1].

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

$$di_d/dt = v_d/L_{ds} - (r_s/L_{ds})i_d + (L_{qs}/L_{ds})\omega_e i_q \quad (4)$$

$$di_q/dt = (1/L_{qs})v_q - (r_s/L_{qs})i_q - (L_{ds}/L_{qs})\omega_e i_d - (\psi_f \omega_e/L_{qs}) \quad (5)$$

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

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.

Table I. Parameters of Wind Turbine and Generator

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	0.48
Swept area	78.5 m^2
Turbine rated speed	167 rpm
Rated power	20 kW
frequency	50 Hz
Pole pairs	18
R_s	0.5Ω
L_s	0.00448 mH

III. 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.

A. 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

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

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

$$C_1 = 1/f_r R\, R_f$$

B. 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 Fig. 2.

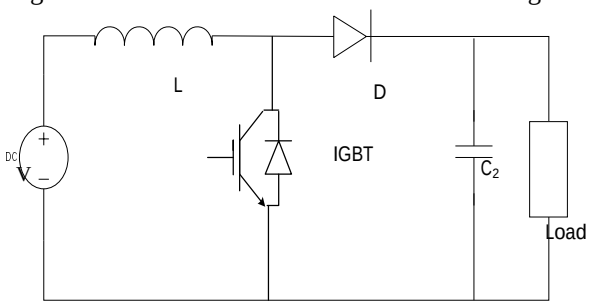


Fig. 2. Circuit diagram of DC-DC boost converter

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

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

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

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

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

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 Fig. 3.

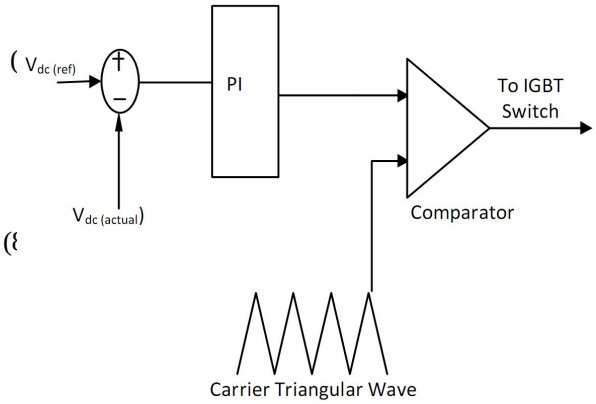


Fig. 3. Block diagram of typical DC-DC boost converter controller

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.

IV. 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. 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.

$$V_o = DV_1 \quad (13)$$

$$M_{VDC} = V_o / V_I = I_I / I_o = D \quad (14)$$

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

$$C_3 = D_{\max}/(2f_s r_c) \quad (16)$$

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, 566V 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 Fig. 4.

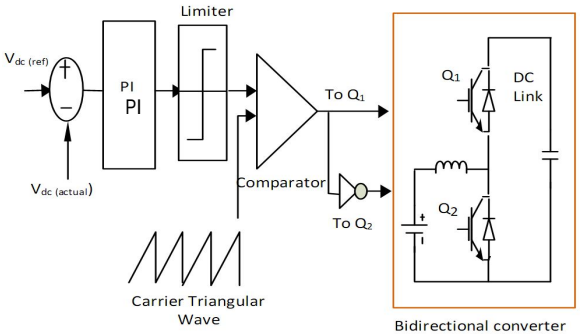


Fig. 4. Block diagram of typical DC-DC bidirectional buck-boost converter controller

V. 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. The battery bank voltage can be kept lower than the reference DC link voltage (566 V) via DC-DC bidirectional buck-boost PWM converter and hence less number of batteries need to be connected in series. In the simulink model, the battery bank voltage is kept at 300V for this system which can continuously supply 10 kW load nearly two 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, 83.33 Ah rating) are needed to connect in series to get the battery bank voltage.

VI. 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. 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

$$P_o = E^2/2R \quad (17)$$

The RMS value of line voltage is

$$V_{L(RMS)} = E/\sqrt{2} \quad (18)$$

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. This unwanted high frequency harmonics can be eliminated by using a simple passive LC filter to prevent the problems in power quality at the customer load. Pulse Width Modulation (PWM) control strategy is used to control the output load voltage during variation of wind speed. The inverter control circuit is shown in Fig. 5. 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.

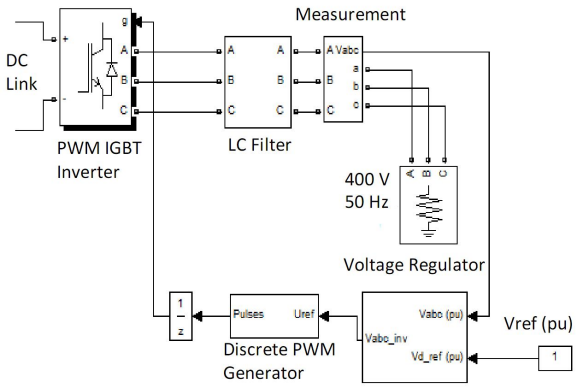


Fig. 5. Block diagram of load side inverter controller

The IGBT inverter uses Pulse Width Modulation (PWM) at a 1 kHz carrier frequency. The load voltage is regulated at 1 pu (400 V) by a PI voltage regulator using abc-to-dq and dq-to-abc transfomations. The output of the voltage regulator is a vector containing the three modulating signals used by the PMW generator to generate the six IGBT pulses. The output voltage of the inverter is to maintain 400 V, 50 Hz.

VII. SIMULATION MODEL AND RESULTS OF THE PROPOSED SYSTEM

The proposed control strategy for the stand-alone variable speed wind energy supply system is simulated in MATLAB/SIMULINK under different operating

conditions. Fig. 6, shows the simulation block diagram for the system.

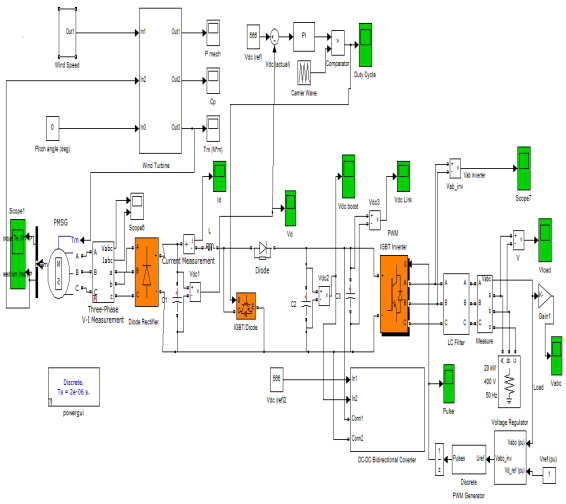


Fig. 6. Simulation model of variable speed stand-alone wind energy supply system

The simulated results of generator output voltage and current according to the wind speed changes are shown in Fig. 7. The results show the fluctuated geneator output voltage and current when the wind speed vary between the turbine cut-in and rated wind speed. When the wind speed is lower than the rated speed, the turbine generator cannot produce the rated power. To generate rated power at low wind speed, the voltage is need to be step up. Therefore, DC-DC boost converter is used to get stable DC link voltage. Fig. 8, shows the output voltage of diode rectifier. It can be seen that the output voltage of diode rectifier is 540 V at the wind speed of 10.5 m/s and it decreases when wind speed is low. The duty cycle of the IGBT switch of DC-DC boost converter is shown in Fig. 9. When the wind speed is higher, the on time of the IGBT switch is smaller. At the low wind speed, the on time of the IGBT switch is large. The output voltage of the DC-DC boost converter shows that the output voltage of the boost converter is nearly stable at 566 V as in Fig.10.

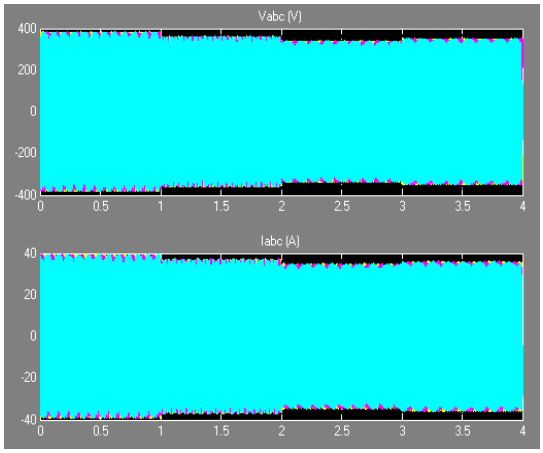


Fig. 7. Simulation result of generator output voltage and current

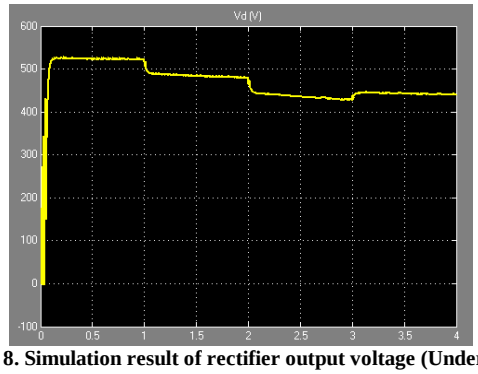


Fig. 8. Simulation result of rectifier output voltage (Under the wind speed variation between cut-in and rated speed)

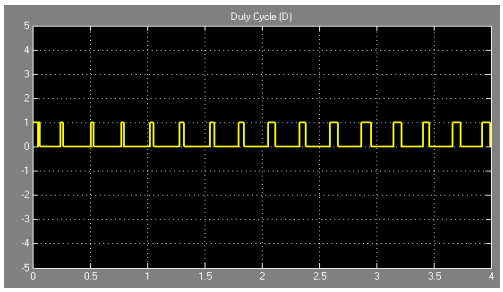


Fig. 9. Simulation result of duty cycle of the boost converter

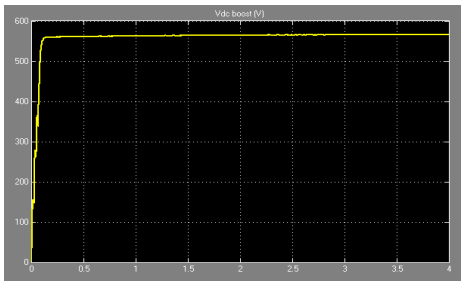


Fig. 10. Simulation result of DC-DC boost converter output voltage

Fig. 11, illustrates the performance of DC-DC bidirectional buck-boost converter. 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. Therefore, switch (Q_2) is on and (Q_1) is off resulting the battery not to be charged but to discharge the store energy.

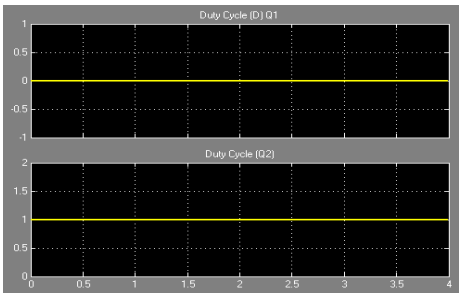


Fig. 11. Simulation result of duty cycle of the IGBT switch (Q_1) and (Q_2)

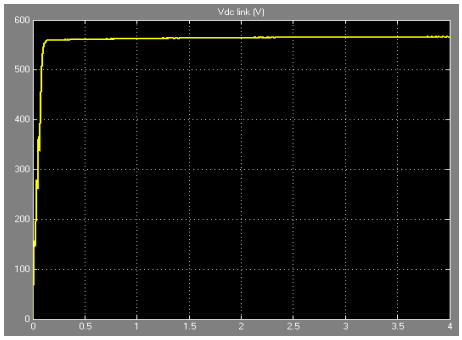


Fig. 12. Simulation result of DC link voltage

The inverter output voltage is shown in Fig. 13 (a), and it can be seen clearly that the inverter produces the PWM wave as shown in Fig. 13 (b). The harmonics generated by the inverter are filtered by the LC filter. After passing the LC filter, the stable sine wave output load voltage is received. The load voltage is shown in Fig. 14 (a) 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 Fig. 14 (b).

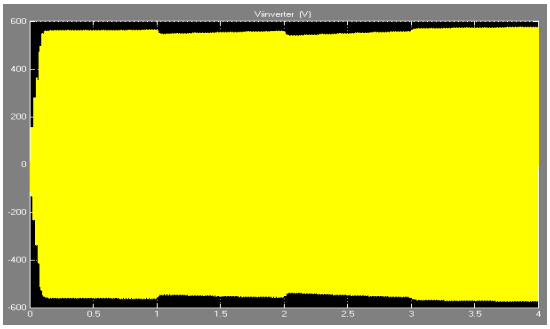


Fig. 13. (a) Simulation result of inverter output voltage

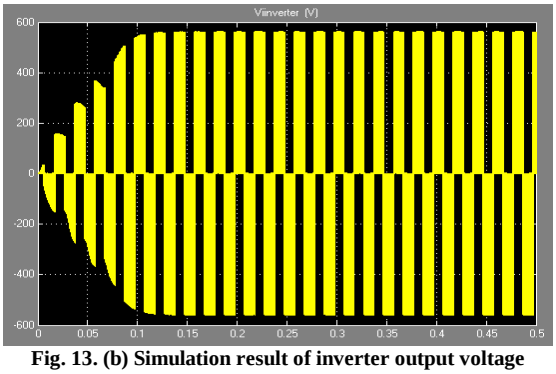


Fig. 13. (b) Simulation result of inverter output voltage

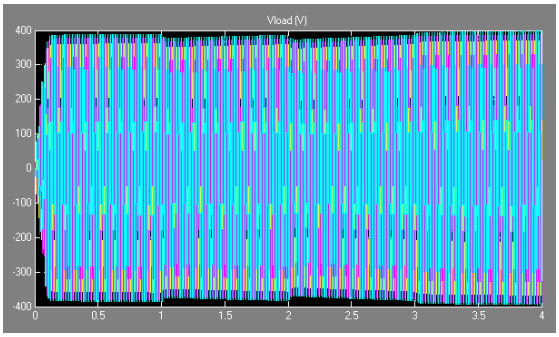


Fig. 14. (a) Simulation result of load supply voltage

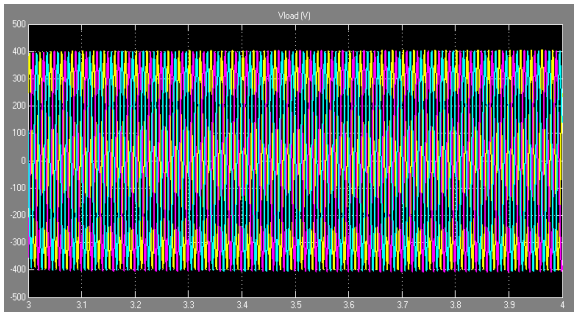


Fig. 14. (b) Simulation result of load supply voltage

CONCLUSION

The proposed system can be a possible solution for remote places that the utility grid is not available. This type of wind turbine system can be used where the available average monthly wind speed is above 5 m/s. The simulation results show the control scheme of the proposed system obtain and maintain the DC link stable voltage at 566 V from the available wind power when the wind speed variations kept between cut-in and rated speed. The battery bank voltage (300V) is kept lower than the reference DC link voltage via DC-DC bidirectional buck-boost PWM converter and hence less number of batteries is need to be connected in series. Through the three phase voltage source inverter, the stable voltage (400V) is supplied to the 18 kW load by controlling the inverter with PWM control technique.

ACKNOWLEDGMENT

The author is deeply gratitude to Dr. Myint Thein, Pro-rector, Mandalay Technological University, for his guidance and advice. The author would like to thank to Dr. Khin Thu Zar Soe, Associate Professor, Head of Department of Electrical Power Engineering, Mandalay Technological University, for her kind permission, providing encouragement and giving helpful advices and comments. The author would like to express her most sincere gratitude and appreciation to Dr. Lwin Za Kyin, Associate Professor, Department of Electrical Power Engineering, Mandalay Technological University, for her valuable expertise, advices, and precious insights have been a source of this work and providing guidelines. The author would like to express her deepest thanks to Dr. Yan Aung Oo, Associate Professor, Department of Electrical Power Engineering, Mandalay Technological University, for his effective advices and helpful discussions.

REFERENCES

[1] Mittal, R.; Sandhu, K.S.; Jain, D.K.Battery energy storage systemfor variable speed driven PMSG for wind energy conversion. Int. J. Innov. Manag. Tech. 2010, 1, 300–304.

[2] Mahmoud M. Hussein ,Tomonobu Senjyu , Mohamed Orabi, Mohamed A. A. Wahab, Mohamed M. Hamada, "Control of a Stand-Alone Variable Speed Wind Energy Supply System", Appl. Sci, pp.437-456 Vol.3, April,2013.

[3] Bhanu R. Bhattatai; "Analysis of a Wind Power Storage System for Load Matching", August 2009

[4] Hugo Eduardo Mena Lopez, "Maximum Power Tracking Control Scheme for Wind Generator Systems", Dec, 2007.

[5] Zaiming Fan,"Mathematical Modelling of Grid Connected Fixed-Pitch Variable-Speed Permanent Magnet Synchronous Generators for Wind Turbines", Jun, 2012.

[6] Muller, S.; Deicke, M.; de Doncker, R.W. Doubly fed induction generator system for wind turbines. IEEE Ind. App. Mag. 2002, 8, 26–33.

[7] Fan, L.; Miao, Z.H.; Wang, X. Sensor less Maximum Power Point Tracking in Multi-Type Wind Energy Conversion Systems. In Proceeding of the 48th IEEE Conference on Decision & Control, Shanghai, China, 15–18 December 2009; pp. 6823–6828.

[8] Modelling and Control design for DC-DC converter, Power Management group, AVLSI Lab, IIT-Kharagpur.

[9] M. Annamalai, Member, IEEE, Dr. M. Vijaya Kumar, Life Fellow, ISTE "Design Simulation of Cll Resonant Dc-To-Dc Converter for Stand Alone Wind Energy System,'' Oct, 2010.

★★★