Wind Energy Conversion System with Boost Converter and CHB MLI with single DC input

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Abstract — **The developments in power electronics technology have led to the developments in the wind energy conversion system (WECS). The output voltage of the WECS depends on the speed of the wind, which is not constant. Hence, a power conversion unit is required to maintain the output voltage of the WECS constant. This paper presents the design of a boost converter and a voltage controller for maintaining the DC-link voltage of the system constant. A new topology of the cascaded H-bridge multilevel inverter (CHB MLI) is proposed for the DC/ AC conversion. The proposed topology eliminates the requirement of separate DC sources. The multilevel inverter is controlled by the selective harmonic elimination pulse width modulation (SHE-PWM) technique. The system is simulated in MATLAB/ Simulink for varying wind speeds. The simulated waveforms of the PMSG rotor speed, the PMSG voltage, the boost converter voltage and the CHBMLI voltages are shown and the results obtained are found to be satisfactory.**

Keyword - Wind Energy Conversion System, Boost Converter, PI Controller, Cascaded H-Bridge Inverter

I. INTRODUCTION

Research is being carried out in the WECS to meet the energy demand. The advantages of the wind energy are that it is cost effective, pollution free, and safe. It has proven to be the best choice among the renewable energy sources. The developments of the power electronic converters have increased the generation of electrical energy by WECS. This has introduced new challenges in the transmission and the distribution systems. The wind energy is obtained by the system consisting of a wind turbine, a generator, a power electronic converter and a control system [1]. Power electronic converters play a vital role in obtaining high efficiency and good performance of the WECS. Initially, WECS were of the fixed speed type with squirrel cage induction generators. In the fixed speed type, the speed of the wind turbine is constant irrespective of the wind speed and is determined by the frequency of the grid. The fixed speed WECS are designed to achieve the maximum output only at one speed [1]. Today, variable speed wind energy systems are popular with the permanent magnet synchronous generator (PMSG) and the doubly-fed induction generator (DFIG). Variable speed wind turbines have many advantages like increased energy capture, operation at the maximum power point, higher efficiency, and improved power quality [2]. The advantages of the variable speed WECS with the PMSG are i) it can be directly connected to the wind turbine without any gear arrangement and ii) it does not require any excitation and hence no slip rings are required resulting is lower cost [3]. The PMSGs are classified as radial flux PMSGs, axial flux PMSGs and transverse flux PMSGs based on the direction of the flux lines. They are also classified as surface inset PMSGs, surface mounted PMSGs and interior PMSGs based on the location of the permanent magnets on the rotor [4]. The surface mounted PMSG is the most efficient compared to other types.

The output voltage of the wind generator is a variable one as the wind speed is not constant. The voltage of the wind generator is less for lower wind speeds and more for higher wind speeds. However, it is necessary to maintain the output voltage constant to make it suitable for any application. A boost converter is designed to maintain the voltage at the constant value by a PI based voltage controller.

The paper is arranged as follows: section II deals the wind energy conversion system, section III explains the simulation and results and the section IV brings out the conclusion.

II. WIND ENERGY CONVERSION SYSTEM

Fig. 1 shows the block diagram of the WECS with a PMSG, a diode bridge rectifier, a boost converter, a CHB MLI, and a three-phase load. The PMSG converts the wind energy into electrical energy, which is fed to the diode bridge rectifier. The rectified DC output is given to the boost converter, which operates in closed loop to obtain the output voltage at the desired value. The output of the boost converter is fed to the three-phase five-level CHB inverter, which feeds a three-phase load.
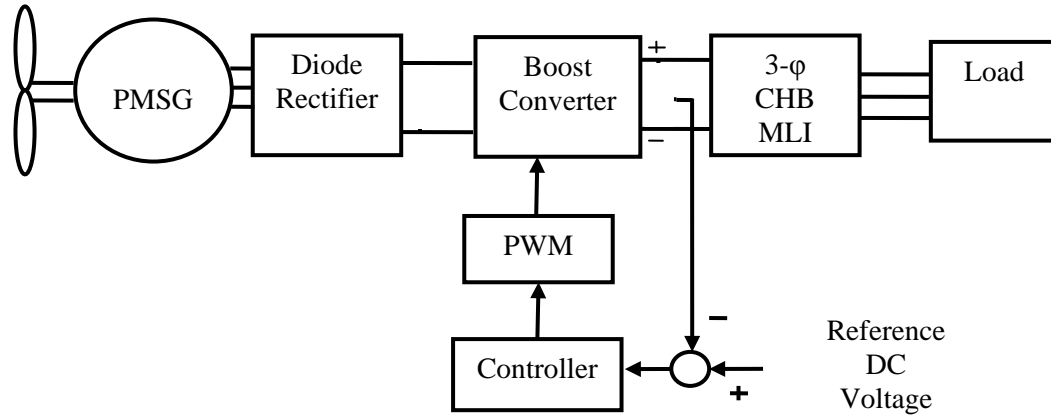
Fig. 1 Block diagram of the wind energy conversion system

A. Wind Turbine

The wind turbine converts the kinetic energy of the wind into mechanical energy. Eqn. (1) gives the power extracted by the rotor of the wind turbine from the wind

$$P_w = \frac{1}{2} c_p \rho A v^3 \tag{1}$$

where, C_p is the power co-efficient, ρ is the air density, A is the swept area of the wind turbine rotor, and v is the wind speed. Eqn. (2) gives the aerodynamic torque of the wind turbine

$$\tau_w = \frac{P_w}{\omega} \tag{2}$$

where, ω is the speed of the rotor in radians per second.

B. Permanent Magnet Synchronous Generator

The permanent magnet synchronous generator (PMSG) converts the mechanical energy of the turbine into electrical energy. In the d-q modelling of the PMSG in the rotor reference frame, the d-axis is aligned with the permanent magnet axis. Eqns. (3) and (4) give the stator voltages in the d-q reference frame.

$$v_d = R_s i_d - \omega_e L_q i_q + \frac{d(L_d i_d)}{dt} \tag{3}$$

$$v_q = R_s i_q + \omega_e (L_d i_d + \psi_{pm}) + \frac{d(L_q i_q)}{dt} \tag{4}$$

Eqn. (5) gives the electromagnetic torque of the PMSG

$$T_e = \frac{3p}{2} (\psi_d i_q - \psi_q i_d) \tag{5}$$

where, $\psi_d = L_d i_d + \psi_{pm}$, $\psi_q = L_q i_q$ and p is the number of pairs of poles. Eqns. (6) and (7) give the active and reactive powers respectively [6].

$$P = \frac{3}{2} (v_d i_d + v_q i_q) \tag{6}$$

$$Q = \frac{3}{2} (v_q i_d - v_d i_q) \tag{7}$$

C. Diode Bridge Rectifier

The diode rectifier converts the three-phase AC voltage of the PMSG into DC voltage. Eqn. (8) gives the average output voltage of the rectifier

$$V_{oavg} = \frac{3\sqrt{3}V_{mph}}{\pi} \qquad (8)$$

where, V_{mph} is the peak value of the phase voltage of the PMSG.

D. Boost Converter

The boost converter converts the rectified DC voltage into DC voltage of the desired magnitude. The boost converter operates in the continuous conduction mode. Fig. 2 shows the circuit of the boost converter. There are two modes of operation for the boost converter. In mode 1, the switch is ON, the diode is in the OFF condition and the inductor stores energy. During this period, the capacitor supplies the output current. In mode 2, the switch is in the OFF condition, the capacitor stores energy and the energy stored in the inductor gets dissipated. Eqn. (9) gives the average output voltage of the converter (V_{DCB}). Eqns. (10) and (11) give the design equations for the boost converter.
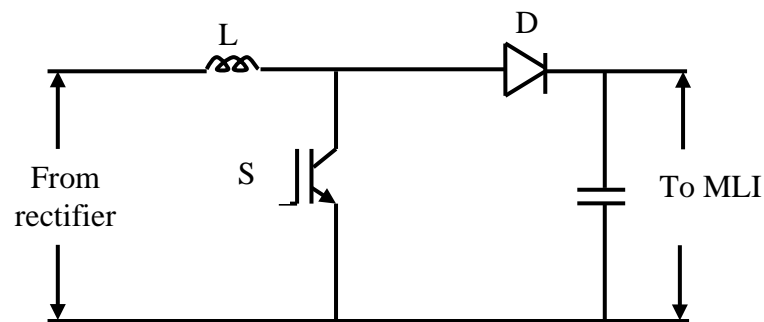

Fig. 2 Circuit of the boost converter

$$V_{DCB} = \frac{V_{oavg}}{(1-k)} \qquad (9)$$

$$L = \frac{kV_{oavg}}{f_s \Delta I} \qquad (10)$$

$$C = \frac{kI}{f_s \Delta V_c} \qquad (11)$$

ΔI is the peak to peak ripple current of the inductor, ΔV_c is the peak to peak ripple voltage of the capacitor, k is the duty ratio of the switch S and f_s is the switching frequency.

E. Proposed CHB Multilevel Inverter

The output of the interleaved boost converter is given to the multilevel inverter. Multilevel inverters (MLIs) are used in renewable energy applications for boosting the low source voltage to a higher voltage for transmitting the power to loads or to grid. They have higher efficiency, lower electromagnetic interference effects, lower switching losses, reduced dv/dt, higher voltage capability and better power quality as compared to the conventional inverters [7]-[9]. There are mainly three configurations of MLIs namely the cascaded H-bridge (CHB), the neutral point clamped and the flying capacitor. The neutral point clamped inverter requires clamping diodes and capacitor whereas the flying capacitor inverter requires capacitors. Of these, the CHB inverter is better for high power applications as it does not require any clamping diodes or capacitors. It achieves the high voltage by cascading multiple single-phase inverter modules and requires the least number of components [10]-[12].

The conventional CHB multilevel inverter uses identical H-bridges in cascade. With the increase in the number of H-bridges, the output voltage waveform becomes more sinusoidal and hence the Total Harmonic Distortion (THD) value decreases. For an m-level inverter, there are ($\frac{m-1}{2}$) identical H-bridges. In addition,

each individual H-bridge requires a separate DC source [13]. The proposed MLI eliminates the disadvantage of using separate DC sources. Fig. 3 shows the circuit of the proposed three-phase five-level CHB MLI. The inverter uses a single DC source irrespective of the number of levels of the inverter. It uses ($\frac{m-1}{2}$) number of transformers for the m-level inverter.
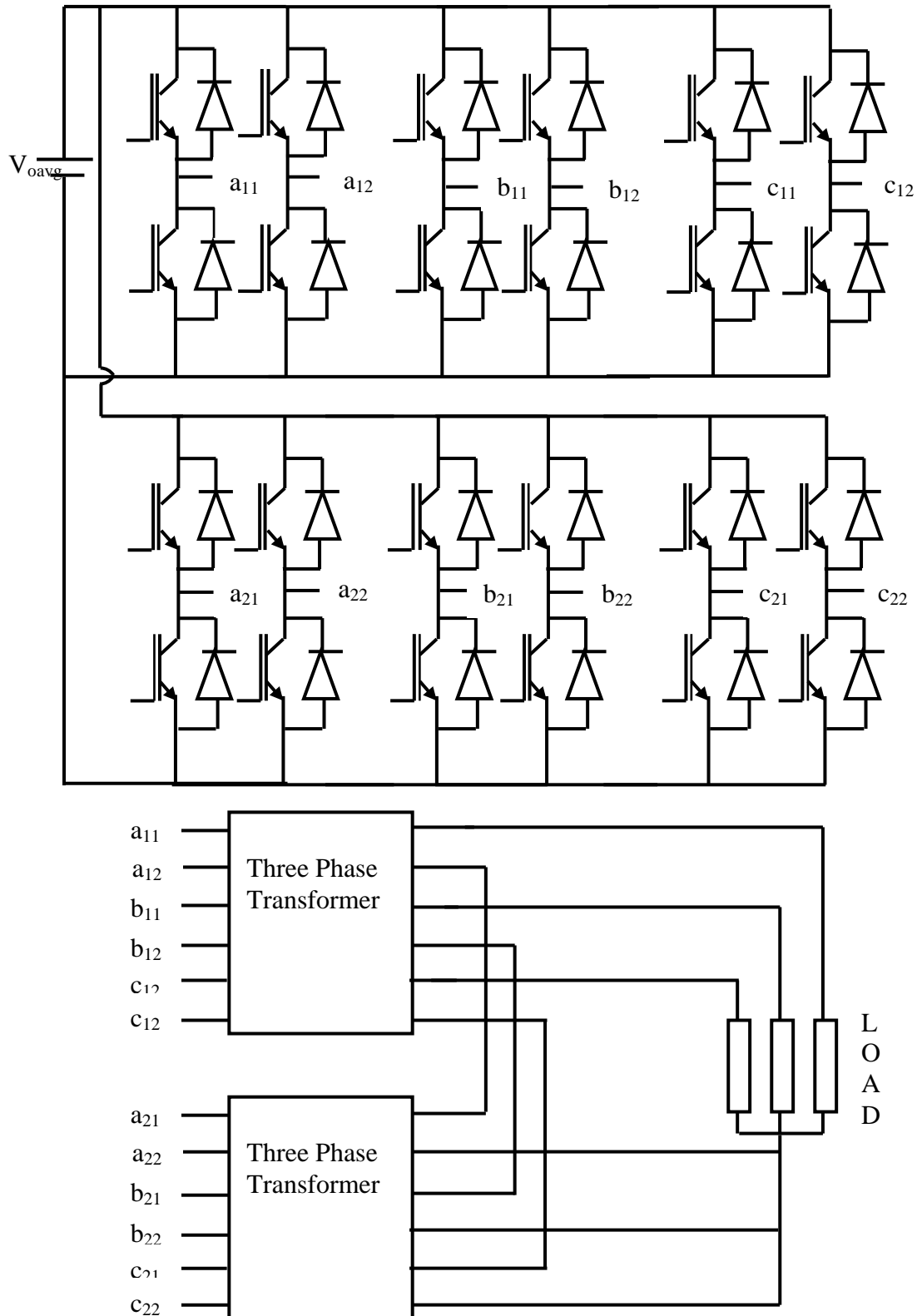

Fig. 3 Circuit of the proposed three-phase five-level MLI

The multi-carrier PWM technique is the most popular for the MLIs. However, for this technique, high frequency carrier signals are required which increases the switching losses. However, it is desired to have the switching at the fundamental frequency. The selective harmonic elimination (SHE) technique produces the desired fundamental value with the elimination of the dominant lower harmonics [14-16]. In this technique, the switching angles are computed by solving transcendental equations characterizing the harmonics [17-18]. For a five-level inverter, two switching angles are generated by solving two transcendental equations using the Newton - Raphson method, one of the fastest iterative methods. This method solves the transcendental equations with initial approximate values. The output voltage waveform of the five-level inverter, which is a staircase waveform, can be expressed using the Fourier series, as given by equation (12)

$$v_n(2\pi ft) = \sum_{n=1,3,5}^{\infty} \frac{4V_{DCB}}{n\pi}(\cos(n\,\theta_1) + \cos(n\,\theta_2))\sin(n2\pi ft) \tag{12}$$

where, θ_1, θ_2 are the switching angles for the five-level inverter, and $0 < \theta 1 < \theta 2 < \pi/2$. From Eqn. (4), the fundamental voltage is given by Eqn. (13).

$$V_1 = \frac{4V_{DCB}}{\pi}(\cos(\theta_1) + \cos(\theta_2)) \tag{13}$$

The maximum value of the fundamental voltage is $V_{m1} = \frac{4sV_{DCB}}{\pi}$, i.e., the value of the fundamental voltage when all the switching angles are zero, where, $s = (m-1)/2$. Modulation index M_I is the ratio of the fundamental voltage to the maximum fundamental voltage, $M_I = \frac{V_1}{V_{m1}}$. Two equations as given by Eqns. (14) and (15) can be formed and the third harmonic equation can be equated to zero to eliminate the third harmonic.

$$\cos(\theta_1) + \cos(\theta_2) = \frac{\pi V_1}{4V_{DCB}} \tag{14}$$

$$\cos(3\theta_1) + \cos(3\theta_2) = 0 \tag{15}$$

The switching angles are found by solving Eqns. (14) and (15) by the Newton-Raphson method. Hence, the third harmonic can be eliminated.

F. Voltage Controller

The proportional integral (PI) controller is used to control the boost converter voltage at the reference value. The output of the PI controller has two parts, one part being proportional to the error signal and the other part being proportional to the integral of the error [19]. Eqn. (16) gives the transfer function of the PI controller [20].

$$G(S) = K_p + \frac{K_i}{s} \tag{16}$$

The controller is tuned using the Ziegler-Nichol's second method of tuning. The various steps involved in this method of tuning are as follows:

1. The system is run with zero integral gain (K_i). The value of proportional gain (K_p) is increased from zero to a critical value K_{crit} until constant magnitude of the sustained oscillation is obtained.
2. The proportional gain K_{crit} and the period of the sustained oscillation T_{crit} are obtained.
3. The controller gains are found by the Eqns. (17)-(19).

$$K_P = 0.45K_{crit} \tag{17}$$

$$T_i = \frac{T_{crit}}{1.2} \tag{18}$$

$$K_i = \frac{K_P}{T_i} \tag{19}$$

III. SIMULATION AND RESULTS

The system is simulated in the MATLAB/ Simulink for varying wind speeds. Figs. 4-9 show the simulated waveforms of the rotor speed of the PMSG, the PMSG voltage, the boost converter voltage, the line voltages and the phase voltages of the CHB-MLI. Fig. 4 shows the PMSG rotor speed. Fig. 5 shows the 'a' phase voltage of the PMSG. It is seen from Figs. 4 and 5 that the rotor speed of the PMSG changes due to the change in wind

speeds at times t = 2.5 s, 5s, 7.5s, the PMSG voltage also changes at t=2.5s, 5s, 7.5s. Fig. 6 shows the output voltage of the boost converter and Fig. 7 shows the line voltage of the MLI. Fig. 8 shows the phase voltage of the MLI.
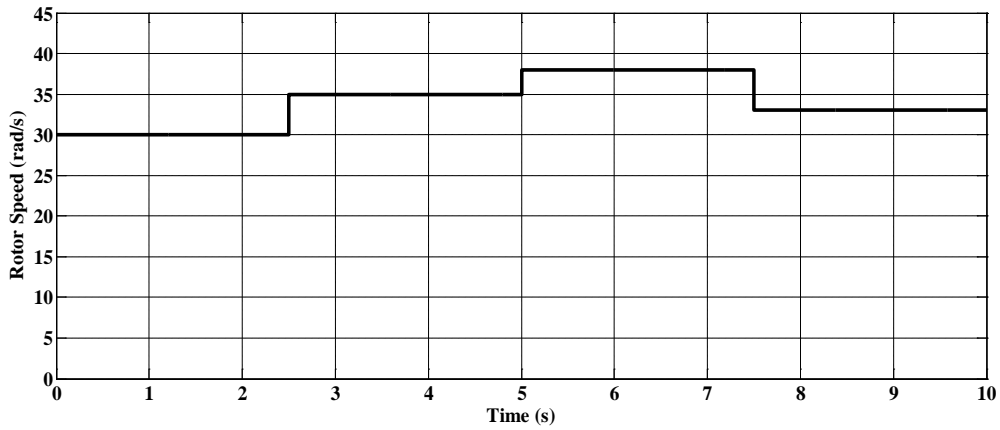

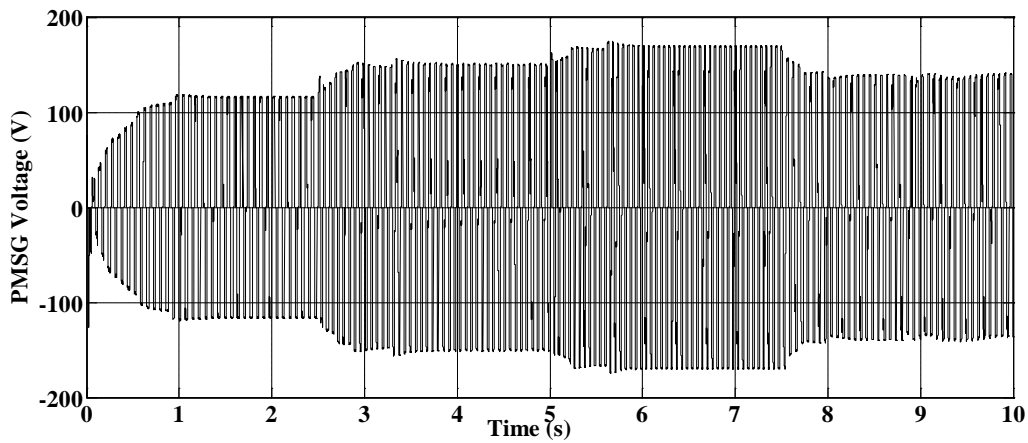Fig.4. Rotor speed of the PMSG
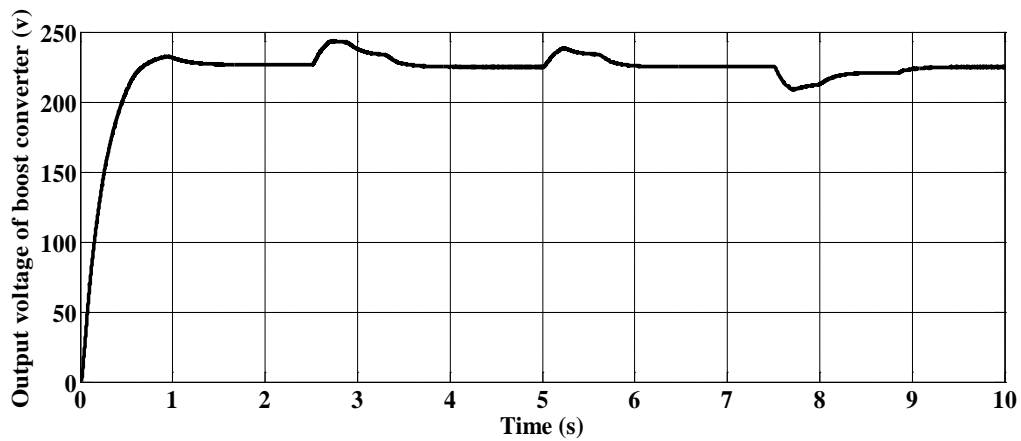

Fig.5. Phase 'a' voltage of the PMSG
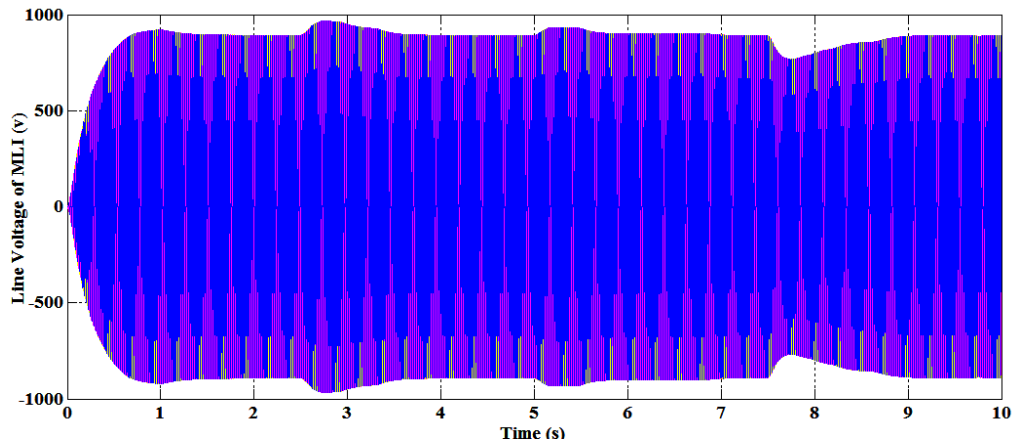

Fig. 6 Boost converter voltage
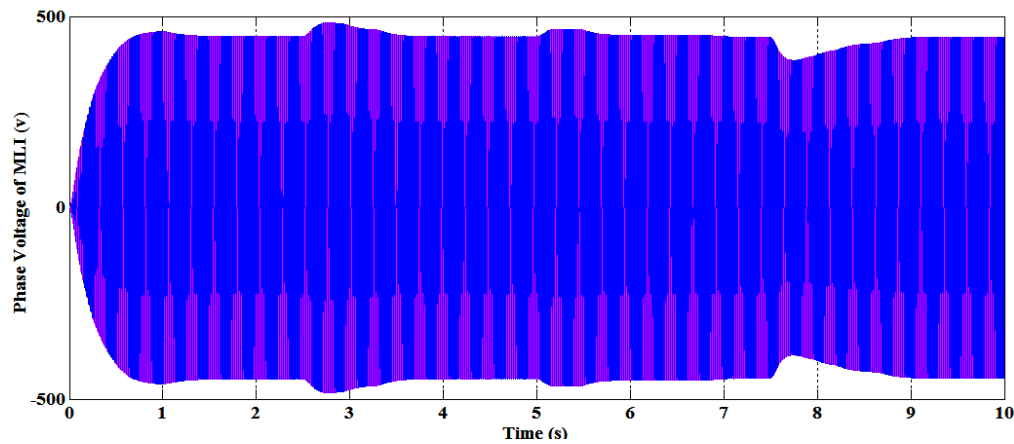
Fig. 7 Line voltages of the MLI

Fig. 8 Phase voltages of the MLI

From Fig. 6 it is seen that the boost converter voltage, after having changed at 2.5 s, 5 s, and 7.5 s due to the change in the PMSG voltage, reaches the reference DC voltage of 225 V in 3.5 s, 5.7 s and 9 s respectively. The line and phase voltages of the MLI also settle to the constant value at 3.5 s, 5.7 s and 9 s respectively, after having changed at 2.5 s, 5 s, and 7.5 s. Fig. 9 shows the phase voltages of the MLI in the expanded scale.
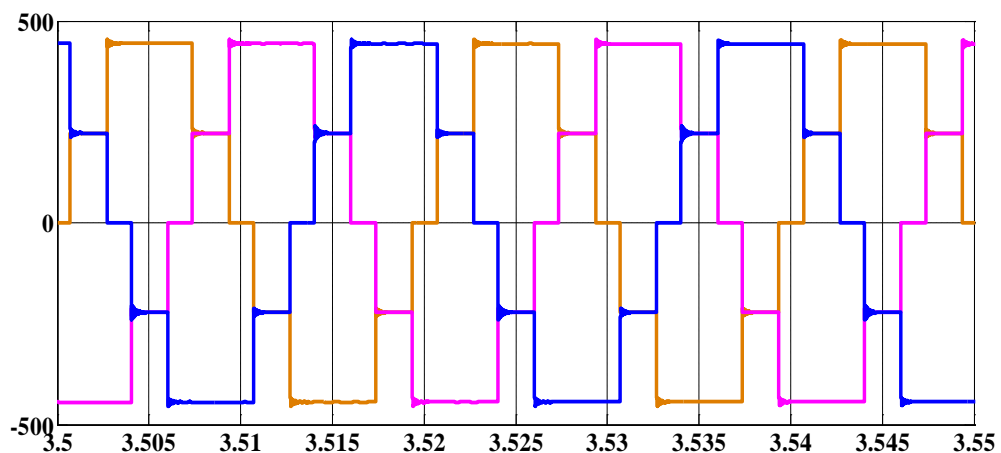

Fig.9. Phase Voltage of the MLI in expanded scale

IV. CONCLUSION

The wind energy system is modeled with the PMSG in MATLAB/ Simulink. A boost converter is designed to step up or step down the voltage for decreasing or increasing wind speeds. A voltage controller is designed to maintain the DC output voltage of the boost converter at a constant value. A new topology of the CHB-MLI which eliminates the requirement of separate DC sources is proposed. The MLI is switched ON with the SHE-PWM. The system is simulated in the MATLAB for varying wind speeds, and the simulated waveforms are obtained for the rotor speed of the PMSG, the PMSG voltage, the boost voltage, the line and the phase voltages of MLI. From the waveforms, it is noted that the designed boost converter and the PI controller are able to maintain the DC voltage at the desired value.

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