Renewable Energy Sources Based Permanent Magnet Brushless DC Motor Drive

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Abstract

A novel permanent magnet brushless DC motor drive using Z – source inverter by PV cell is proposed and analyzed in this paper. This drive system provides advantages both for PMBDC motor and Z – source inverter. The operation principle, system configuration and control method are presented in this paper and it explores methods for the Z-source inverter and their relationships of voltage boost versus modulation index. A maximum boost control (MBC) is presented to produce the maximum voltage boost (or voltage gain) under a given modulation index. The mathematical model of the drive system is established based on the equivalent circuit. Simulation results prove the desired features of the drive system.

Keywords: renewable energy source (RES), PV cell, Permanent magnet brushless dc motor (PMBLDC), Z – source inverter, maximum boost control (MBC).

I. INTRODUCTION

Photovoltaic (PV) power generation is becoming more promising since the introduction of the thin film PV technology due to its lower cost, excellent high temperature performance, low weight, flexibility, and glass-free easy installation [1]. However, there are still two primary factors limiting the widespread application of PV power systems. The first is the cost of the solar cell/module and the interface converter system; the second is the variability of the output of the PV cells.

A PV cell's voltage varies widely with temperature and irradiation, but the traditional voltage source inverter (VSI) cannot deal with this wide range without over rating of the inverter, because the VSI is a buck converter whose input dc voltage must be greater than the peak ac output voltage [2]-[3]. A transformer and a dc/dc converter is usually used in PV applications, in order to cope with the range of the PV voltage , reduce inverter ratings, and produce a desired voltage for the load or connection to the utility. Many pulse-width modulation (PWM) control methods have been developed and used for the traditional three-phase voltage-source (V-source) inverter.

The traditional V-source inverter has six active vectors (or switching states) when the dc voltage is impressed across the load and two zero vectors when the load terminals are shorted through either the lower or upper three devices.The recently presented Z source inverter [1]–[3] has additional zero vectors: shoot-through switching states that are forbidden in the traditional V-source inverter. For the traditional V-source inverter, both switches of any phase leg can never be gated on at the same time or a short circuit (shoot through) would occur and destroy the inverter. The new Z-source inverter advantageously utilizes the shoot through states to boost the dc bus voltage by gating on both upper and lower switches of a phase leg.

Therefore the Z-source inverter can boost voltage and produce a desired output voltage that is greater than the available dc bus voltage. In addition, the reliability of the inverter is greatly improved because the shoot through due to mis-gating can no longer destroy the circuit. Thus it provides a low-cost, reliable, and high efficiency single stage structure for buck and boost power conversion.

This paper investigates the PMBDCM drive system fed by a PV cell through Z-source inverter. Firstly, the configuration, operation principle and control method of proposed electric drive system are described. Then the mathematical modeling for PMBLDC motor and MBC. Finally, simulation results are carried out to verify the desired performance of the proposed drive systems.

II. PV CELL BASED PMBDC MOTOR DRIVE SYSTEM BY Z – SOURCE INVERTER

The Z-source inverter (ZSI) has been reported suitable for residential PV system because of the capability of voltage boost and inversion in a single stage to PV power generation systems. By using the new Z-source topology, the inverter draws a constant current from the PV array and is capable of handling a wide input voltage range. It also features lower component ratings and reduced source stress compared to the traditional ZSI

To fully utilize the zero states so as to minimize the voltage stress across the device, maximum boost control turns all traditional zero states into shoot-through state[5]. Indeed, turning all zero states into shoot-through state can minimize the voltage stress; however, doing so also causes a shoot-through duty ratio varying in a line cycle, which causes inductor current ripple.

This will require high inductance for low-frequency or variable-frequency applications. Maximum Boost Control (MBC) turns all traditional zero states into shoot-through zero state. The PWM signals with the use of the MBC maintains the six active states unchanged and turns all zero states into shoot-through zero states.

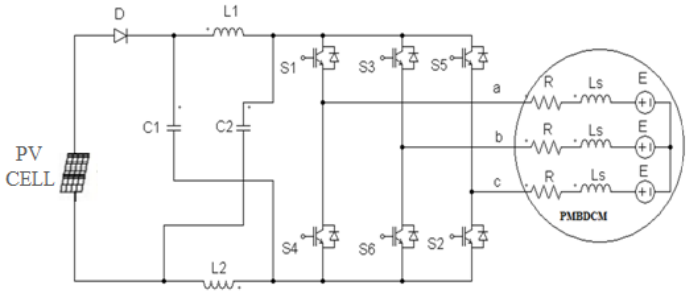

Fig. 1.1: PV cell source inverter based PMLDC MOTOR

Fig. 1 shows the main circuit of the proposed renewable energy source based PMBDCM drive system. Brushless DC motors, rather surprisingly, is a kind of permanent magnate synchronous motor[6]. Permanent magnet synchronous motors are classified on the basis of the wave shape of their induce emf, i.e, sinusoidal and trapezoidal. The sinusoidal type is known as permanent magnet synchronous motor; the trapezoidal type goes under the name of PM Brushless dc (BLDC) machine. Permanent magnet (PM) DC brushed and brushless motors incorporate a combination of PM and electromagnetic fields to produce torque (or force) resulting in motion. This is done in the DC motor by a PM stator and a wound armature or rotor.

Current in the DC motor is automatically switched to different windings by means of a commutator and brushes to create continuous motion. In a brushless motor, the rotor incorporates the magnets, and the stator contains the windings. As the name suggests brushes are absent and hence in this case, commutation is implemented electronically with a drive amplifier that uses semiconductor switches to change current in the windings based on rotor position feedback. In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor.

III. MACHINE DYNAMIC MODEL

The BLDCM[7] has three stator windings and a permanent magnet rotor on the rotor. Rotor induced currents can be neglected due to the high resistivity of both magnets and stainless steel. No damper winding are modeled the circuit equation of the three windings in phase variables are obtained.

$$\begin{bmatrix}\begin{bmatrix}Vas\\Vbs\\Vcs\end{bmatrix} = \begin{bmatrix}Rs & 0 & 0\\0 & Rs & 0\\0 & 0 & Rs\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}L & M & M\\M & L & M\\M & M & L\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + \begin{bmatrix}ea\\eb\\ec\end{bmatrix}\end{bmatrix} \text{.....(1)}$$

where V_{as} , V_{bs} and V_{cs} are the stator phase voltages,R_s is the stator resistance per phase, i_a , i_b and i_c are the stator phase currents, L_{aa} , L_{bb} and L_{cc} are the self-inductance of phases a, b and c, L_{ab},L_{bc} ,and L_{ca} are the mutual inductances between phases a, b and e_a, e_b and e_c are the phase back electromotive forces .It has been assumed that resistance of all the winding are equal. It also has been assumed that there is no change in the rotor reluctance with angle because of a non salient rotor and then

$$L_{aa} = L_{bb} = L_{cc} \quad \text{---------- (2)}$$

$$L_{ab} = L_{ba} = L_{bc} = L_{cb} = L_{ca} = L_{ac} = M \quad \text{---------- (3)}$$

There fore in state space from

$$\begin{bmatrix}\begin{bmatrix}Vas\\Vbs\\Vcs\end{bmatrix} = \begin{bmatrix}Rs & 0 & 0\\0 & Rs & 0\\0 & 0 & Rs\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}L-M & 0 & 0\\0 & L-M & 0\\0 & 0 & L-M\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + \begin{bmatrix}ea\\eb\\ec\end{bmatrix}\end{bmatrix} \text{.....(4)}$$

where V_{as} ,V_{bs} and V_{cs} are phase voltages and may be designed as

$$V_{as} = V_{ao} - V_{no},$$

$$V_{bs} = V_{bo} - V_{no} \text{ and}$$

$$V_{cs}=V_{co}-V_{no} \quad \text{---------- (5)}$$

where V_{ao},V_{bo},V_{co} and V_{no} are three phase and neutral voltages referred to the zero reference potential at the mid- point of dc link.

The stator phase currents are constrained to be balanced i.e.

$$i_a + i_b + i_c = 0 \quad \text{---------- (6)}$$

This leads to the simplifications of the inductances matrix in the models as then

$$M\, i_a + M\, i_b = -M\, i_c \quad \text{---------- (7)}$$

There fore in state space from

$$\left[\begin{bmatrix} Vas \\ Vbs \\ Vcs \end{bmatrix} = \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} ea \\ eb \\ ec \end{bmatrix}\right] \text{.....(8)}$$

It has been assume that back EMF e_a ,e_b and e_c are have trapezoidal wave form,
Then we can write

$$\left[\begin{bmatrix} ea \\ eb \\ ec \end{bmatrix} = \omega_m * \lambda_m \begin{bmatrix} fas(\theta r) \\ fbs(\theta r) \\ fcs(\theta r) \end{bmatrix}\right] \text{...(9)}$$

Where ω_{mr} the angular rotor speed in radians per seconds, λ_m is the flux linkage, θ_r is the rotor position in radian and the functions $f_{as}(\theta_r)$, $f_{bs}(\theta_r)$, and $f_{cs}(\theta_r)$ have the same shape as e_a , e_b and e_c with a maximum magnitude of ±1.The induced emfs do not have sharp corners because these are in trapezoidal nature. The emfs are the result of the flux linkages derivatives and the flux linkages are continuous Function of rotor position. Fringing also makes the flux density function smooth with no abrupt edges.
The electromagnetic toque in Newton's defined as

$$T_e=[e_a i_a+e_b i_b+e_c i_c]/\omega_m \text{(N-m)} \quad \text{--------(10)}$$

It is significant to observe that the phase voltage-equation is identical to armature –voltage equation of dc machine. That is one of reasons for naming this machine the PM brushless dc machine
The moment of inertia is described as

$$J = J_m + J_1 \quad \text{-------(11)}$$

The equation of the simple motion system with inertia J, friction coefficient B, and load torque T_l is

$$J*(d_{wm})/dt + Bw_m = (T_e - T_1) \quad \text{------- (12)}$$

The electrical rotor speed and position are related by

$$d\theta/dt = p/2*wm \quad \text{------(13)}$$

The damping coefficient B is generally small and often neglected thus the system. The above equation is the rotor position θ_r and it repeats every 2π . The potential of the neutral point with respect to the zero potential (V_{no}) is required to be considered in order to avoid imbalance in the applied voltage and simulate the performance of the drive. This is obtained by substituting equation (6) in the volt-ampere equation (8) and adding then give as

$$V_{ao} + V_{bo} + V_{co} - 3v_{no} = R_s(i_a + i_b + i_c) + (L - M)(pi_a + pi_b + pi_c) + (e_a + e_b + e_c) \quad \text{----------(14)}$$

Where Substituting equation (6) in equation (14) we get

$$V_{ao} + V_{bo} + V_{co} - 3V_{no} = (e_a + e_b + e_c)$$

thus

$$V_{no} = [V_{ao} + V_{bo} + V_{co}] - (e_a + e_b + e_c)/3 \text{ -----(15)}$$

The set of differential equations mentioned in equations (8), (12), and (13) defines the developed model in terms of the variables i_a ,i_b , i_c , ω_m and, θ_r, time as an independent variable. Combining the all relevant equations, the system in state-space form is

$$\dot{X}=AX+BU+CE \quad \text{------(16)}$$

$$X=[i_a \;\; i_b \;\; i_c \;\; w_m \;\; \theta r] \quad \text{-------(17)}$$

Where A=

$$\begin{bmatrix} -\frac{Rs}{L-M} & 0 & 0 & -\frac{\lambda m}{J}fas(\theta r) & 0 \\ 0 & -\frac{Rs}{L-M} & 0 & -\frac{\lambda m}{J}fbs(\theta r) & 0 \\ 0 & 0 & -\frac{Rs}{L-M} & -\frac{\lambda m}{J}fcs(\theta r) & 0 \\ \frac{\lambda m}{J}fas(\theta r) & \frac{\lambda m}{J}fbs(\theta r) & \frac{\lambda m}{J}fcs(\theta r) & -B/J & 0 \\ 0 & 0 & 0 & P/2 & 0 \end{bmatrix} ----(18)$$

$$B = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix} ----(19)$$

$$C = \begin{bmatrix} -\frac{1}{L-M} & 0 & 0 \\ 0 & -\frac{1}{L-M} & 0 \\ 0 & 0 & -\frac{1}{L-M} \end{bmatrix} ----(20)$$

$$U = [Vas \quad Vbs \quad Vcs \quad T1] -----(21)$$

$$E = [ea \quad eb \quad ec]T \quad -----(22)$$

IV. MAXIMUM BOOST CONTROL

A. VOLTAGE BOOST AND STRESS

As described in [4], the voltage gain of the Z-source inverter can be expressed as

$$V_{ac}/(V_o/2)=M*B \quad -------(23)$$

Where V_{ac} is the output peak phase voltage,Vo is the input dc voltage, is the modulation index M, and is the boost factor B, which is determined by

$$B= 1/(1-2*To/T) \quad --------(24)$$

Based on (23) and (24), defines the voltage gain G as

$$G = MB = G/(2G-1) \quad --------(25)$$

For any desired voltage gain G, the maximum modulation index can be used is

$$M =(2-M \sin\theta-M \sin(\theta-2\pi/3))/2 \quad ------(26)$$

As analyzed in [1], the voltage stress Vs across the switches is BVo ,the voltage stress under this modulation method can be calculated by

$$V_s = BV_o = (2G-1)*V_O \quad ---------- (27)$$

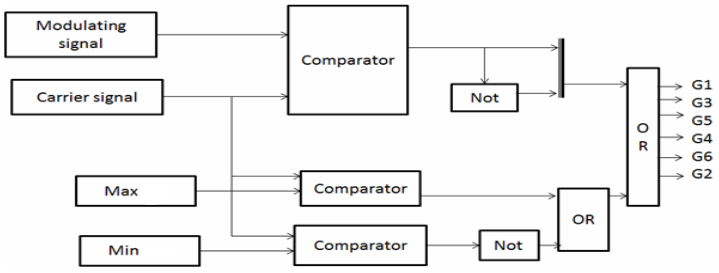

Fig. 4.1: Maximum Boost Control

Fig. 4.1 shows the proposed maximum boost control strategy. It is quite similar to the traditional carrier-based PWM control method. The point is: this control method maintains the six active states unchanged and turns all zero states into shoot-through zero states. Thus maximum To and B are obtained for any given modulation index M without distorting the output waveform. As can be seen from Fig.4.1, the circuit is in shoot through state when the triangular carrier wave is either greater than the maximum curve of the references V_a V_b V_c or smaller than the minimum of the references. The shoot through duty cycle varies each cycle. To calculate the voltage gain, what we are interested in is the average shoot through duty cycle. The shoot through state repeats

periodically every $\pi/3$. Assume that the switching frequency is much higher than the modulation frequency, the shoot-through duty ratio over one switching cycle in the interval can be expressed a

$$\frac{To(\theta)}{T}\ T_o(\theta)/T=(2-M\sin\theta-M\sin(\theta-2\pi/3))/2 \qquad \text{-----(28)}$$

The average duty ratio of shoot-through can be calculated by integrating (28) which yields

$$\frac{To}{T}=\int_{\theta}^{\theta}\frac{2-M\sin\theta-M\sin\left(\theta-\frac{2\pi}{3}\right)}{2}\,d\theta=\frac{2\pi-3\sqrt{3}M}{2\pi}\text{----(29)}$$

From eqn (29), the boost factor B is obtained

$$B=1/(1-2\ T_o/T) \qquad \text{-------- (30)}$$

With this type of control method, the voltage gain can be determined by the modulation index

$$V_{ac}/(V_o/2) \quad =MB=\pi M/(3\sqrt{3}\ M-\pi) \quad \text{------ (31)}$$

From eqn (31) and voltage gain defined in (25), the maximum modulation index that can be used for a given voltage gain is

$$M=\pi G/(3\sqrt{3}\ G-\pi) \qquad \text{------(32)}$$

$$V_s = BV_o = (3\sqrt{3}\ G-\pi)/\pi\ V_o \qquad \text{-----(33)}$$

The detailed analysis is given below.The shoot-through duty ratio can be is calculated as $T_0/T = 0.308$

The boost factor $B = 1/(1-2(T_0/T_1))=2.5930$

Average dc link voltage = $V_{dcl} = V_c = ((1-T_0/T))/((1-2(T_0/T)))* V_{dc} = 456.47V$

Peak dc link voltage = $V_{dcp} = B * V_{dc} = 656.8V$

Peak ac output voltage = $V_{acp}= M * B * V_{dc/2} = 0.8*2.593*253.3/2 = 262.7V$

Output line to line RMS voltage=$\sqrt{3} * V_{ac}= 238V$, The buck-boost factor = $B_B= M * B = 0.8*2.593 = 2.075$

The capacitor voltage = $V_c = 337V$, Gain of inverter, $G =(M /M-1)= 2.075$

V. SIMULINK RESULTS & DISCUSSIONS

Simulation is performed using MATLAB software. Maximum constant boost control method is used for PWM generation and simulation. The component values of Z-source inverter depends on switching frequency only. These component values are chosen as per design guidelines in [1] and [3]. The simulation circuit arrangement is shown in Fig. 5.1.For this circuit $L_1 = L_2=$ 500mH and $C_1 = C_2 =$ 500uF. The purpose of the system is to produce 420Vrms line to line voltage. For PWM[4] generation the carrier frequency is set to 10 KHz and modulating reference signal frequency is set to 50Hz. The modulation index is 0.8 and the input DC voltage of PV cell is 253.3V. The voltage gain of inverter obtained in above analysis is 2.075. As we increase the shoot-through time interval (T_0), the boost factor will increase and this will increase the inverter voltage gain.

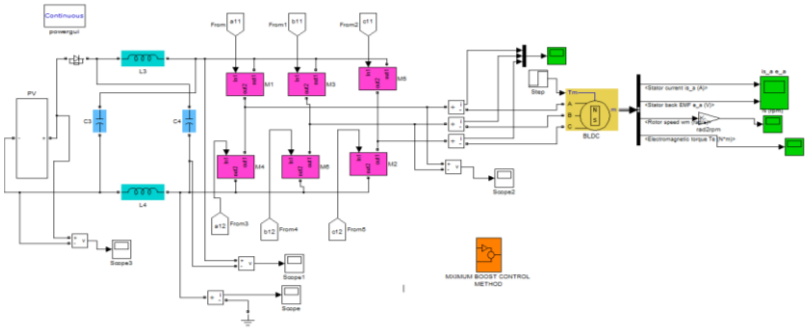

Fig. 5.1: Simulink model for PMBLDC motor with PV cell by MBC method

Table - 1
Load Voltage Profile for Different values of 'M' for PV cellx

Operation Condition	*Input Voltage*	*FFT Analysis*	*Output Voltage*
M=0.88	*253.3*	*1.42%*	*400*
M=0.5	*253.3*	*2.20%*	*250*
M=0.3	*253.3*	*3.43%*	*200*

The simulation results with the same input voltage and carrier frequency are shown in following Figures, which agrees well with the analysis and theoretical results. The PV cell inverter through impedance –network can be operated in both the boosts and buck operations depending on values of 'M'. If M is greater than 0.5 it acts as boost inverter, if less than 0.5then it acts as buck inverter.(Table1)

Fig.5.2 to 5.10 shows the simulation waveforms of the phase current , rotor speed n and electromagnetic torque Te of the PMBDCM. The simulation results with the same input voltage and carrier frequency are shown in following Figures, which

agrees well with the analysis and theoretical results. The PV cell inverter through impedance –network can be operated in both the boosts and buck operations depending on values of 'M' . If M is greater than 0.5 it acts as boost inverter, if less than 0.5then it acts as buck inverte

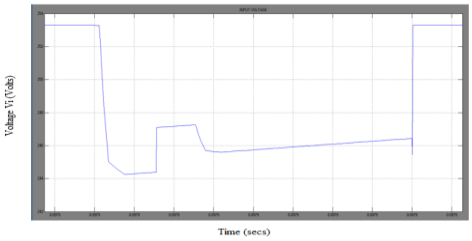

Fig.5.2: Response of input DC voltage (253.3V) versus time

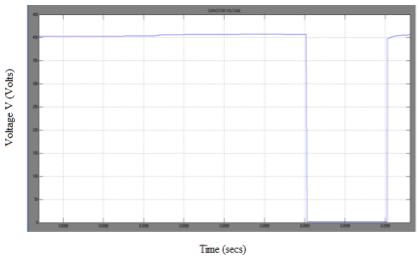

Fig 5.3: Response of Capacitor voltage (401V) versus time

Using triangular function, comparator and adder repeated shoot-through pulses are generated. These shoot through pulses are evenly spread in all the three phase PWM waveform using OR-logic function. The SPWM generator generates normal three phase PWM waveforms for a given carrier frequency and it is shown in Fig 5.4.

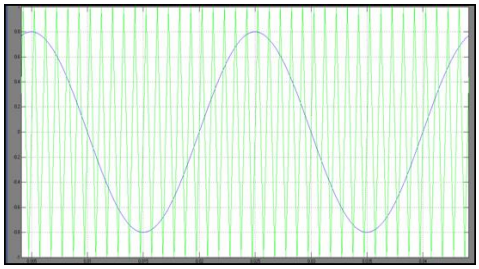

Fig. 5.4: Duty Ratio Profile with standard SPWM

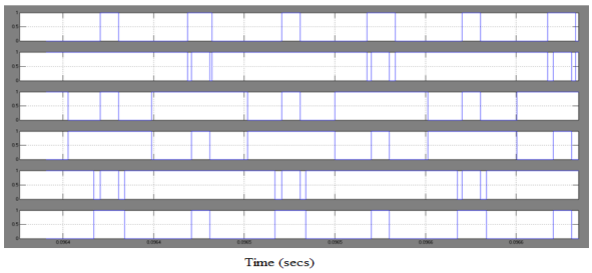

Fig. 5.5: Response of gating signals to 3-Φ inverter by MBC method for PV cell

Three phase stator current waveforms and stator voltage for a given load condition is shown in the Fig 5.6and 5.7 respectively. Stator current waveforms are observed to be very smooth sinusoidal waveform as compared to the traditional PWM inverter

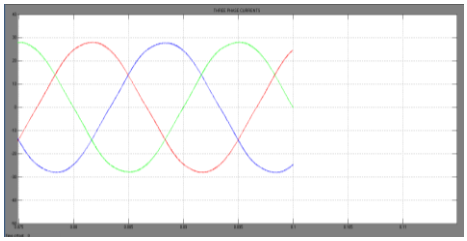

Fig. 5.6: Response of three phase stator current versus time

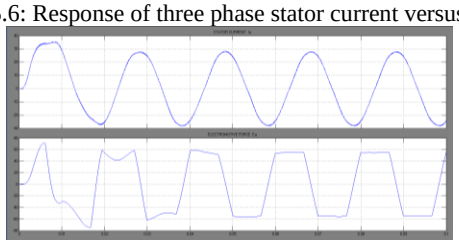

Fig. 5.7: waveforms of stator current and emf by MBC method for pv cell versus time

This is the basic property of the Z-source inverter. Due to this operational behavior, z-source inverter can boost the output voltage to any value greater than input voltage. The simulation result for speed variation of the PMBLDC motor is shown in the following figure 10. Initially speed of motor increase linearly where at that time the motor fetches more current so as to maintain the torque. Under steady state condition the maximum speed of induction motor is observed to be about 750rad/s. In terms of rpm the maximum speed is 1500rpm.

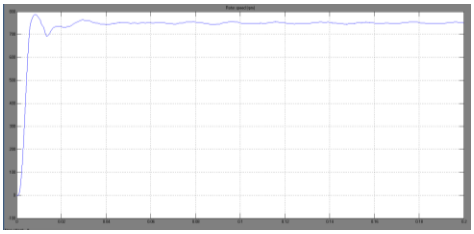

Fig. 5.8: Response of Speed (in rad/sec) for PMBLDC motor by MBC method versus time

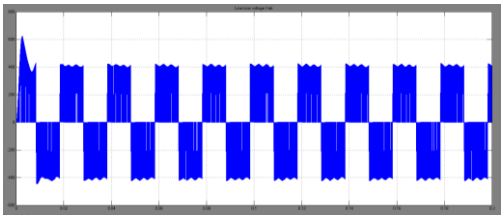

Fig. 5.9: Response of Torque (in n-m) of rotor for PMBLDC motor by MBC method for PV cell versus time

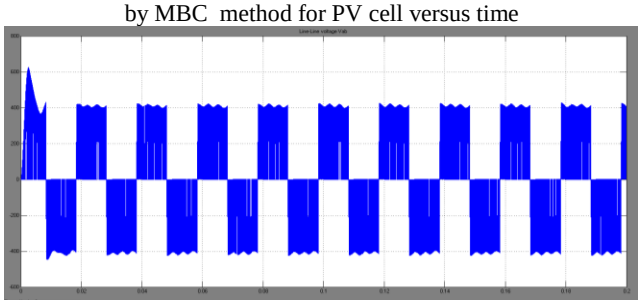

Fig. 5.10: Response of peak dc link voltage across inverter bridge(420V) versus time

VI. CONCLUSION

The performance of a 3-phase permanent magnet motor operating as BLDC motor fed by impedance inverter through PV cell of solar energy was analyzed in this paper. From different PWM techniques, we consider sinusoidal pulse width modulation. In Z-Source inverter the output voltage can be stepped up and down by choosing an appropriate buck–boost factor B. The buck–boost factor is determined by the modulation index M and boost factor B. For Z-source inverter the boost factor is always greater than or equal to unity . Maximum boost control method is more advantageous method among the other PWM control methods and it increases output voltage. It allows over-modulation where modulation index can be varied from 0.57 to 1.154. The entire drive system is simulated using MATLAB/SIMULINK software and results of simulation are observed.

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