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# Modelling and Performance Evaluation of Solar Powered PMBLDC Drive System in MATLAB/Simulink Atmosphere

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**Abstract**: This project deals with modelling and performance evaluation of solar powered BMBLDC drive systems using MATLAB and its toolbox SIMULINK. The system consist of mathematical model of photo voltaic source, boost converter, BLDC motor, inverter, current controller an speed/torque controller is used for proposed model of solar powered PMBLDC drive system. The motor is controlled through a hysteresis current loop and an outer speed loop with a pi type controller. The proportional and integral gains are set to their optimal values. This proposed model can be projected to unproblematic design tool for the development of solar powered PMBLDC drive system.

**Keywords**: PV cell, Boost Converter, BLDC, Switching function.

## I. INTRODUCTION

Renewable energy plays an important role in electricity generation. The main advantage of renewable energy is that it is an indigenous resource available in considerable quantities to all developing nations, in principle of having a significant local, regional or national economic impact. Several renewable options are financially and economically competitive for certain applications such as in conventional fuels remote locations where the cost of transmitting electrical power or transporting conventional fuels are high. Energy from the sun is one of the best options for electricity generation as it is viable for long run and free to harness.

The solar irradiance received on the surface of the PV cells is converted instantaneously into electric power by PV effect. The motor is a machine which transforms the electrical energy into mechanical energy. Conventional DC motors have many attractive properties such as high efficiency, linear torque-speed characteristics and ease to control. However the main drawback of dc motor is the need of periodic maintenance and has other undesirable effects such as spark, acoustic noise and carbon particles coming from the brushes. Brushless DC motors in many cases can replace conventional DC motors.

The BLDC motor has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. In this model the trapezoidal back emf waveforms are modelled as a function of rotor position, so that position can be actively calculated according to the operating speeds. Hysteresis or pulse width modulated (PWM) current controllers are used to maintain the actual currents flowing into the motor as close as possible to the rectangular reference values. Because of the trapezoidal back emf and the consequent number of sinusoidal variation of the motor inductance with rotor angle, transformation of the machine equations to the well-known d,q model is not necessarily the best approach for Modelling and simulation instead, natural or phase variable approach offers many advantages. Here the switching function concept is adopted to model the pwm inverter. This in turn results in obtaining the detailed voltage and current waveforms of the inverter and calculating the design parameters such as average and rms ratings of components.

The power conditioning has a role to optimize the transfer of energy between PV array and load. In this work the boost converter is used to step up the dc voltage received from PV cell. The boost converter is cheaper since it has minimum number of power devices in its circuit.

## II. PHOTOVOLTAIC CELLS

*A.* Equivalent Circuit of PV Module

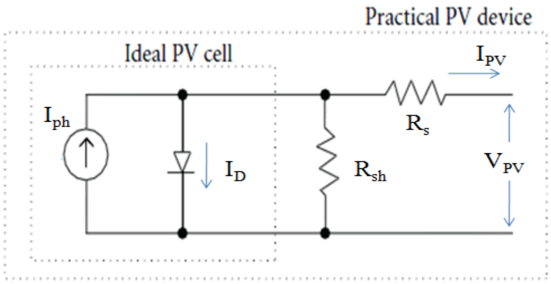


Fig.1. Electrical equivalent circuit of PV module

The equivalent circuit of a PV module is shown in Fig.1. The simplest model of a photovoltaic cell is known under the name of one diode model. It constitutes a diode in parallel with a current source and one or two resistor. $R_s$is the equivalent series resistance of the array and $R_p$ is the equivalent parallel resistance. The shunt resistance is classically neglected. The intensity of the current is directly proportional to the light received by the cell. The current voltage characteristic of the diode depends on temperature. The more the module temperature increases, the less power it can deliver. The basic equation that


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describes the characteristics of the ideal photovoltaic cell is,

$I = I_{PV} – I_D$

Where $I_{pv}$ is the current generated by the incident light and it is shown in fig.2.

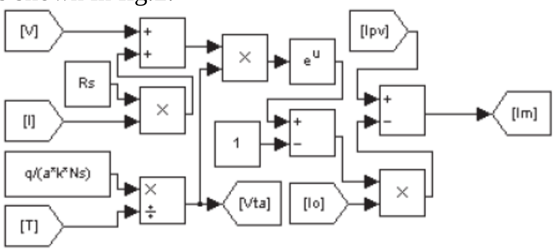


Fig.2.Modelling of current generating block

$I_{pv}$ is directly proportional to the sun irradiation and $I_D$ is the Shockley diode equation which is given by,

$I_D = I_{o,cell}[\exp(qv/akT)] – 1$

Where $I_{o,cell}$ is the reverse saturation or leakage current of the diode[A], q is the electron charge[1.6021e-19 C], k is the Boltzmann constant[1.38065e-23 J/K], T is the temperature of the p-n junction[k], a is the diode ideality constant(1<a<1.6)

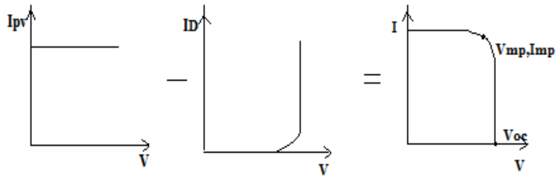


Fig.3. IV characteristic curve of PV

Arrays are composed of several photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation. Basic equation that describes the IV characteristics of the ideal photovoltaic array is

$I = I_{pv} – I_o [\exp((V+R_s)/V_ta)]-(V+R_sI/R_p)$

Where, $V_t = N_skT/q$

$I_{pv}$ and $I_o$ are the photovoltaic and saturation currents of array and $V_t$ is the thermal voltage of the array. This equation originates the IV curve shown in fig.2.where $V_{oc}$ is the nominal open circuit voltage, $I_{sc}$ is nominal short circuit current, $V_{mp}$ is the voltage at the maximum power point, $I_{mp}$ is the current at the maximum power point.

*B.* Photo Current of PV Module

The light generated current or photo current of the photovoltaic cell depends linearly on the solar irradiation and it is also influenced by the temperature according to the following equation,

$I_{pv} = [I_{pv,n} + K_I(T – T_n)][G/G_n]$

T and $T_n$ are the actual and nominal temperatures[k], G is the irradiation on the device surface[W/m$^2$], $G_n$ is the nominal irradiation[W/m$^2$] and $I_{pv}$ is the light generated current at the nominal condition[A].Photo current generating block is shown in fig.4.

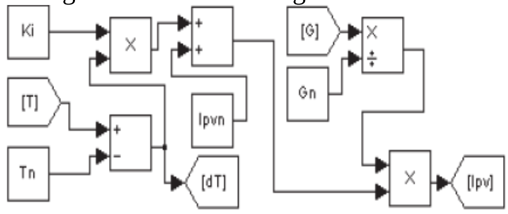


Fig.4. Modelling of photocurrent generating block

*C.* Diode saturation Current

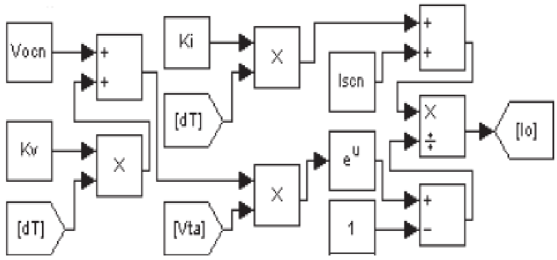


Fig.5. Modelling of diode saturation current

The saturation current $I_o$ of the photovoltaic cells which is shown in fig.5, which compose the device depends on the saturation current density of the semiconductor ($J_o$ generally given in [A/cm$^{2]}$ and on the effective area of the cells.

$I_o=[(I_{sc,n}+K_I\Delta_T)/(\exp(V_{oc,n}+K_v\Delta_T)/aV_t)-1)$

$K_v$ and $K_I$ are the voltage and current coefficients. $I_{sc,n}$is the short circuit current, $V_{oc,n}$ is an open circuit voltage and $V_t$is the thermal voltage of the array. Simulation result of photovoltaic array is shown in fig .6.

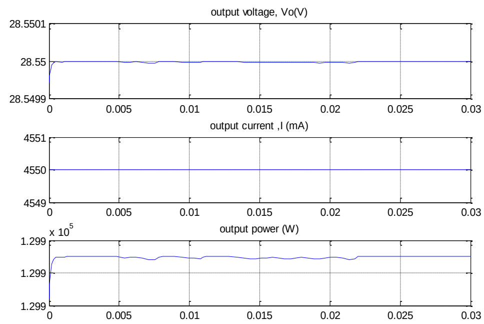


Fig.6. Simulation result of PV array

## III. BOOST CONVERTER

D. Steady State analysis of Boost Converter

Boost converter is a power electronic circuit whose output voltage is greater than the input. It consists of dc input voltage source$V_s$,boost inductor L, controlled switch S, diode D, filter capacitor C and load resistance R. The circuit diagram of boost converter is shown in fig.7.

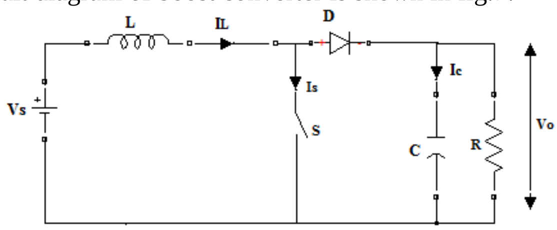



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Fig.7. Ideal boost converter

The state variables for the boost converter are inductor current x1 and capacitor voltage x2. From state space averaging of boost converter, values of output voltage and load current are given by the following equations.

$I_L = \int((V_{in}/L)-(V_o(1-D)/L))$
$V_o=\int((I_L/C)-(V_o(1-D)/C))$

Modelling and simulation of boost converter is shown in fig 8 and 9 respectively. Output voltage reaches the steady state in 0.05 seconds.

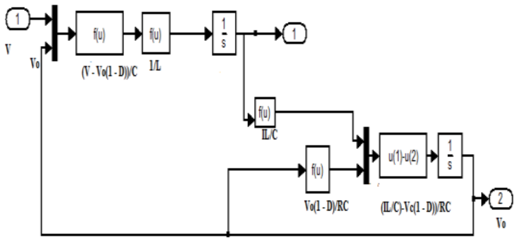

Fig.8.Modelling of boost converter

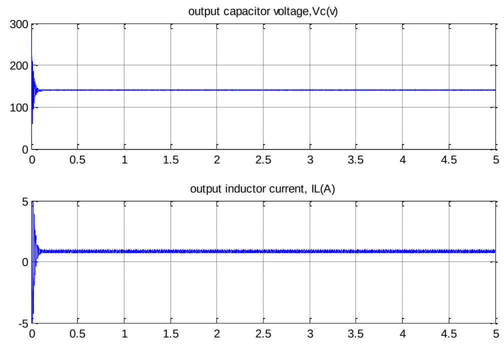


Fig.9. Simulation result of boost converter

## IV. BLDC MOTOR

According to NEMA standard a BLDC motor is a motor having stator windings and a permanent magnet or salient pole soft iron rotor. The stator windings are supplied from a primary dc supply through a matrix of solid state switches which are controlled by rotor shaft position sensors and logic. In the absence of a regulator motor speed is approximately proportional to the primary dc voltage.

### E. Modelling of Brushless DC Motor

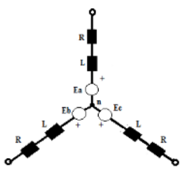

Fig.10. Electrical equivalent circuit of BLDC motor

Electrical equivalent circuit of BLDC motor is shown in fig.10.From fig.10, terminal voltage equation of the BLDC motor can be written as,

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix}$$

On substituting the variable L and M for self and mutual inductance, the above equation becomes,

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + (L-M) \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix}$$

The induced emf $e_{as}$, $e_{bs}$, $e_{cs}$ are all assumed to be trapezoidalwhere $E_p$ is the peak value which is given by, $E_p=(Blr\omega_m N)$, where B is the flux density, l is the length of the conductor, r is the radius of rotor, $\omega_m$ is angular velocity and N is the number of conductors. If we substitute for flux then$\varphi_a$ = Blr and flux linkage$\lambda_p$=N$\varphi_a$ then $E_p = \lambda_p\omega_m$. The voltage equation per phase is,

$$V_{as} = i_a R_s + (L-M)\frac{d}{dt} i_a + e_{as}$$

In steady state the current is constant hence the rate of change of current is zero. For power balance $i_a$is multiplied on both sides. Now voltage equation becomes,

$$V_{as} i_a = i_a^2 R_s + e_{as} i_a$$

The term $i_a^2 R_s$denotes the stator copper loss and $V_{as}i_a$ is input power and $e_{as}i_a$ is the air gap power $P_a$.
$P_a= T_{ep}\ \omega_{m=}\ e_{as}i_a$

Therefore the total electromagnetic torque for all the three phase is given by,

$$T_e = (e_{as}i_a + e_{bs}i_b + e_{cs}i_c) \,/\, \omega_m$$

The instantaneous induced emf can be written as,

$$e_{as} = f_{as}(\theta_r)\lambda_p\omega_m$$
$$e_{bs} = f_{bs}(\theta_r)\lambda_p\omega_m$$
$$e_{cs} = f_{cs}(\theta_r)\lambda_p\omega_m$$

Where the function $f_{abcs}(\theta_r)$ have the same wave shape as $e_{abcs}$ with a maximum magnitude of +1 and -1 then electromagnetic torque is,

$$T_e = \lambda_p[f_{as}(\theta_r)i_a + f_{bs}(\theta_r)i_b + f_{cs}(\theta_r)i_c]\text{Nm}$$

For simplicity, load is modelled as moment of inertia J, viscous friction coefficient B. then accelerating torque $T_a$ drives the load.

$$J\frac{d\omega_m}{dt} + B_1\omega_m = T_e - T_l = T_a$$

$T_l$ is the load torque which constitutes the dynamic model of BLDC motor.

F. Modelling and Implementation of BLDC using Matlab

The proposed model consists of emf block, load current block, hysteresis current control block, pwm inverter block and speed/torque controller block as shown in fig.11.

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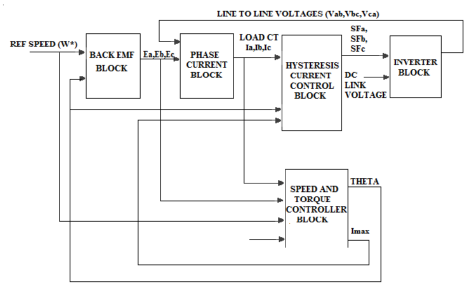

Fig.11. Overall block diagram of BLDC motor

1) Back EMF Block:

The back emf is a function of rotor position and has an amplitude $E=K_e.\omega_r.K_e$ is the back emf constant. Modelling of back emf, shown in fig.12, has theta and E as an input which produces three back emf voltages $e_a$, $e_b$, $e_c$. Simulation is performed under the assumption that all three phase have identical back EMF waveforms. Simulation output based on the rotor position is shown in fig. 12 and 13. The numerical expression of the back emf can be obtained as shown below.

$$e_a = \begin{cases} (6E/\pi)\theta_r & (0 < \theta_r < \pi/6) \\ E & (\pi/6 < \theta_r < 5\pi/6) \\ -(6E/\pi)\theta_r + 6E & (5\pi/6 < \theta_r < 7\pi/6) \\ -E & (7\pi/6 < \theta_r < 11\pi/6) \\ (6E/\pi)\theta_r - 12E & (7\pi/6 < \theta_r < 11\pi/6) \end{cases}$$

$$e_b = \begin{cases} -E & (0 < \theta_r < \pi/2) \\ (6E/\pi)\theta_r - 4E & (\pi/2 < \theta_r < 5\pi/6) \\ E & (5\pi/6 < \theta_r < 9\pi/6) \\ -(6E/\pi)\theta_r + 10E & (9\pi/6 < \theta_r < 11\pi/6) \\ E & (11\pi/6 < \theta_r < 2\pi) \end{cases}$$

$$e_c = \begin{cases} E & (0 < \theta_r < \pi/6) \\ -(6E/\pi)\theta_r + 2E & (\pi/6 < \theta_r < \pi/2) \\ -E & (\pi/2 < \theta_r < 7\pi/6) \\ (6E/\pi)\theta_r - 8E & (7\pi/6 < \theta_r < 9\pi/6) \\ E & (9\pi/6 < \theta_r < 2\pi) \end{cases}$$

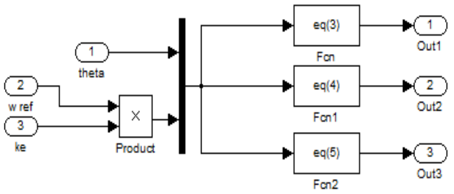

Fig.12. Simulink model of emf block

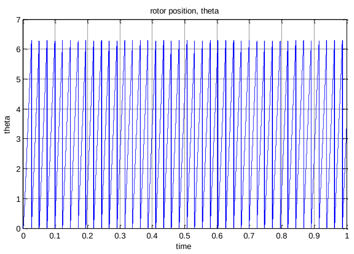

Fig.13. Simulation result of rotor position, theta

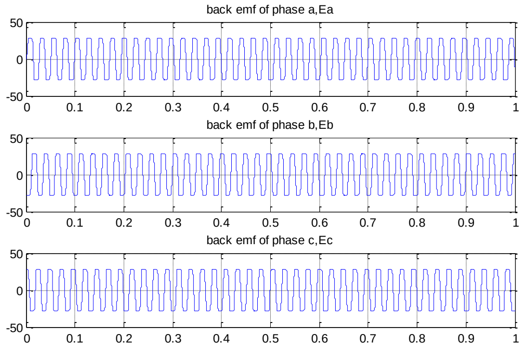

Fig.14.Simulation result of emf block

2) Speed and Torque Control Block:

Speed and torque characteristics of the BLDC motor shown in fig.16, can be explained with the following equation. On neglecting the damping factor we get,

$\omega_m=(1/J)\int(T_e-T_l)=(1/J)\int[(T_{ea}+T_{eb}+T_{ec})-T_l]dt$

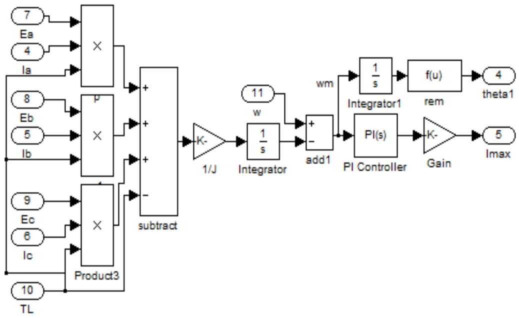

Fig.15.Simulink model of speed and torque

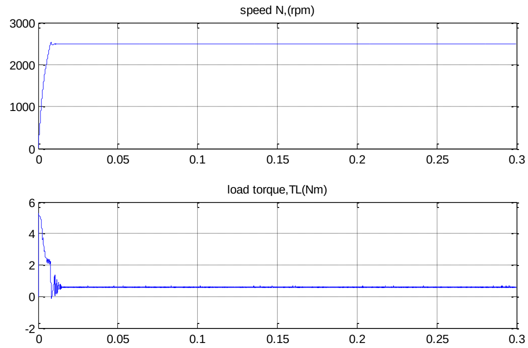

Fig.16.Simulation result of speed and torque block

3) Hysteresis Current Control block:

In the BLDC motor hysteresis current control technique can be regarded as the main current control strategies. $I_a$, $I_{max}$, $\theta_r$are the inputs to thefunction block which in turn outputs the three switching functions $SF_a$, $SF_b$, $SF_c$. Simulink model and switching functions for the three phases are shown in fig.17 and 18.This current control method is explained based on the case of phase A.

Case1: $I_a$>0
Period1: $I_a$ < LL= switch S1 is turned on.
Period2: $I_a$>UL= switch S1 is turned off and D4 is conducted.

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Period3: LL < $I_a$< UL and $dI_a/dt>0$= S1 is on.
Period4: LL < $I_a$< UL and $dI_a/dt<0$=S1 is off and D4 is conducted.

Case2: $I_a<0$
Period1:$I_a$ > UL= switch S4 is on.
Period2:$I_a$ < LL= switch S4 is off and D1is conducted.
Period3:LL < $I_a$ <UL and $dI_a/dt<0$ = S4 is on.
Period4:LL < $I_a$< UL and $dI_a/dt>0$=S1 is off and D1 is conducted.

Here UL and LL are upper and lower limits respectively. This hysteresis current control logic is realized in a function block $f_a$ (u) using the mathematical model given below.

$$f_a(u) = (D > \pi/6)\cdot(D < 5\pi/6)$$
$$\begin{bmatrix} (A < C * 0.9) - (A > C * 1.1) \\ + (A > C * 0.9) * (A < C * 1.1) * (A > B) \\ -(A > C * 0.9) * (A < C * 1.1) * (A < B) \end{bmatrix} +$$
$$(D > 7\pi/6)\cdot(D < 11\pi\ /\ 6)$$
$$\begin{bmatrix} -(A > -C * 0.9) + (A < -C\ * 1.1) \\ -(A < -C\ * 0.9) *\ (A > -C * 1.1) * (A < B) \\ +(A < -C * 0.9) *\ (A > -C * 1.1) * (A > B) \end{bmatrix}$$

Where A = u[1], B = u[2], C = u[3], D = u[4]. A represents $I_a$, B represents previous value of $I_a$, C represents upper(1.1) and lower limit(0.9) of $I_a$, D represents rotor position.

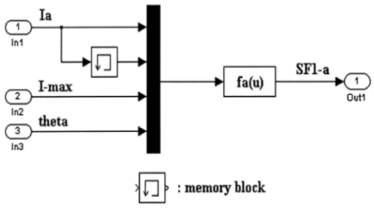


Fig.17.Simulink model of switching function generating block of phase a

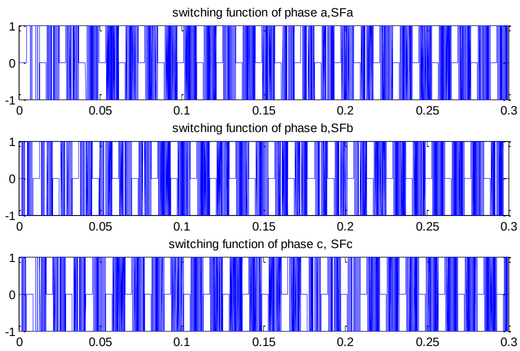


Fig.18. Simulation result of switching functions

4)PWM Inverter Voltage and Current Generating Blocks:
From the hysteresis block switching functions $SF_{1\_a}$, $SF_{1\_b}$, $SF_{1\_c}$, are determined to model the operation of pwm inverter. Using switching function concept, power conversion circuit can be modelled according to their functions rather than circuit topologies. As we know in BLDC motor only two phases are excited though the conduction operating modes. Therefore the three phase currents are considered in terms of line to line voltages. From fig.10.voltage and current equations can be obtained as follows.

$$v_{ab} = R_{LL}i_1 + (L - M)_{LL}\frac{di_1}{dt} + e_{ab}$$
$$v_{ab} = R_{LL}i_1 + (L - M)_{LL}\frac{di_1}{dt} + e_{ab}$$
$$v_{bc} = R_{LL}i_2 + (L - M)_{LL}\frac{di_2}{dt} + e_{bc}$$
$$v_{ca} = R_{LL}i_3 + (L - M)_{LL}\frac{di_3}{dt} + e_{ca}$$

Where, $R_{LL}$ = 2R and $(L\text{-}M)_{LL}$ = 2(L - M)
Back emf, $e_{ab} = e_a - e_b$
$e_{bc} = e_b - e_c$,
$e_{ca} = e_c - e_a$

And phase current, $i_a = i_3 - i_1$
$i_b = i_2 - i_1$
$i_c = i_3 - i_2$

Using switching function $SF_{1\_abc}$ which is obtained from hysteresis block, inverter line to line voltage can be derived as,

$$v_{ab} = v_{ao} - v_{bo} = \frac{v_d}{2}(SF_{1\_a} - SF_{1\_b})$$
$$v_{bc} = v_{bo} - v_{co} = \frac{v_d}{2}(SF_{1\_b} - SF_{1\_c})$$
$$v_{ca} = v_{co} - v_{ao} = \frac{v_d}{2}(SF_{1\_c} - SF_{1\_a})$$

Duty cycle controlled PWM voltage and current can be obtained from the Simulink model shown in fig.19 and 22 and its result is displayed in fig.20 and 21. Fig.23, shows the back emf and phase current are in well synchronization with each other as per Hysteresis Control Algorithm.

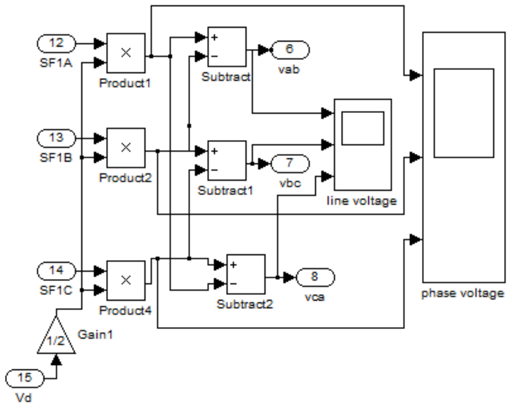


Fig.19. Simulink model of voltage generating block

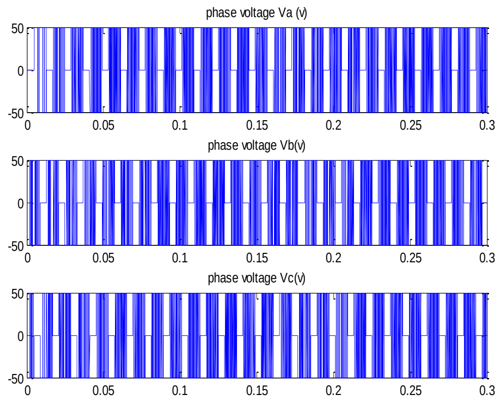


Fig.20.Simulation result of phase voltage generating block

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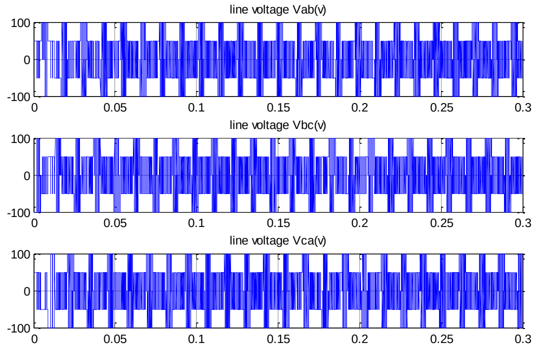


Fig.21.Simulation result of phase voltage generating block

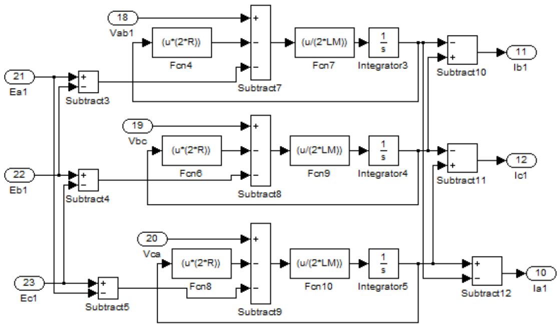


Fig.22.Simulink model of phase current generating block

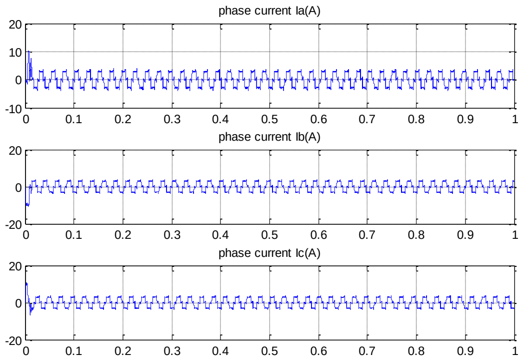


Fig.23.Simulation result of phase current generating block

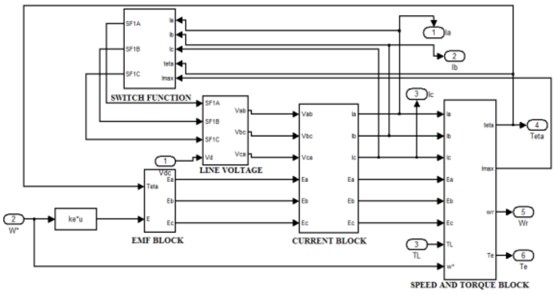


Fig.24. Modelling of BLDC motor

G. Simulation Result of PV Fed PMBLDC

Simulation results of PV fed PMBLDC motor for constant speed of 261 rad/sec and with a step change in 100rad/sec are displayed in this section.

1. Output of EMF Block with Respect to Rotor Position for a Constant and Step Change in Speed:

Fig.26 and 28, shows the generated back emf from the rotor position and the phase-current waveforms according to the operating speed. EMF waveforms are actively calculated and generated from the rotor position. Here the rotor speed position is varied from 0 to 2 π per electric cycle and the back EMF has amplitude of 28.11 V. From fig.28, it is clear that as back emf is directly proportional to speed, small step change at 100 rad/sec increases the amplitude of the back emf.

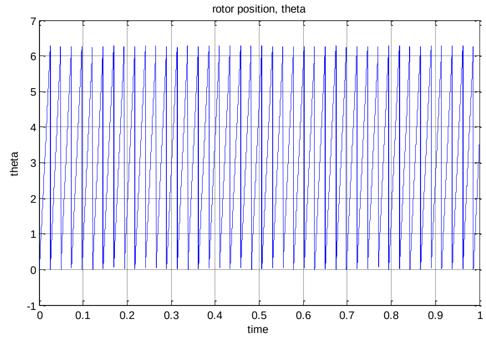


Fig.25. Simulation result of rotor position for constant speed.

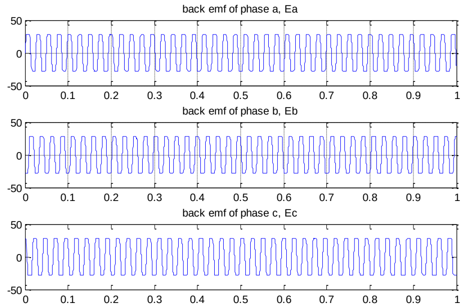


Fig.26. Simulation result of emf block for a constant speed

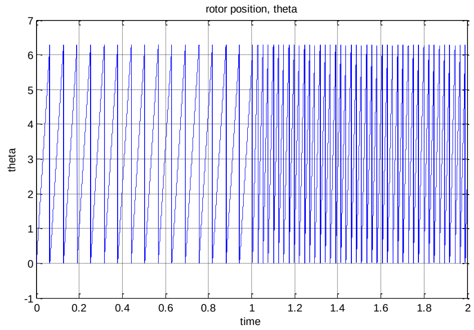


Fig.27 . Simulation result of rotor position for step chnge in speed.

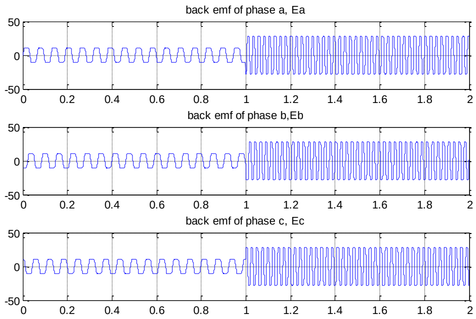


Fig.28. Simulation result of emf block for step change in speed

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2) Output of Speed and Torque Control Block for a Constant and Step Change in Speed:

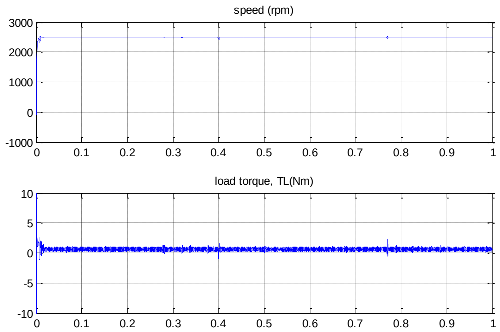


Fig.29. Simulation result of speed and torque block for constant speed

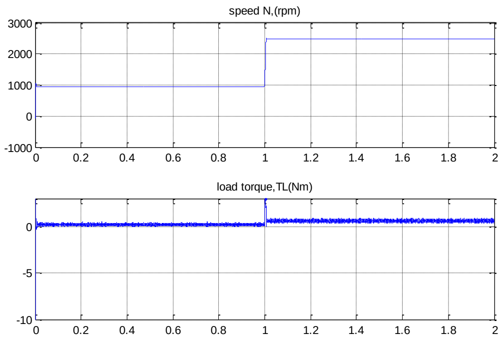


Fig.30. Simulation result of speed and torque block for step change in speed

3) Output of Switching Function for a Constant and Step Change in Speed:

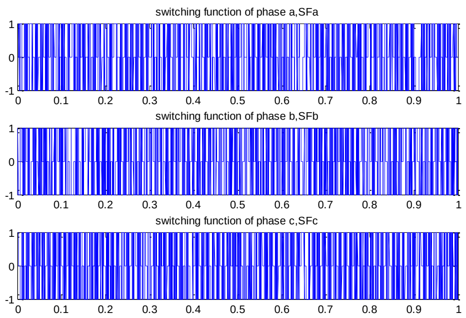


Fig.31. Simulation result of switching functions for constant speed.

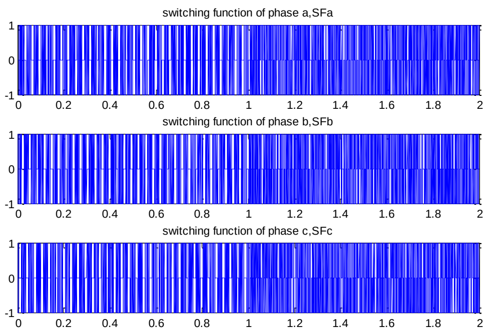


Fig.32. Simulation result of switching functions for step change in speed.

4) Output of Voltage Generating Block for a Constant and Step Change in Speed:

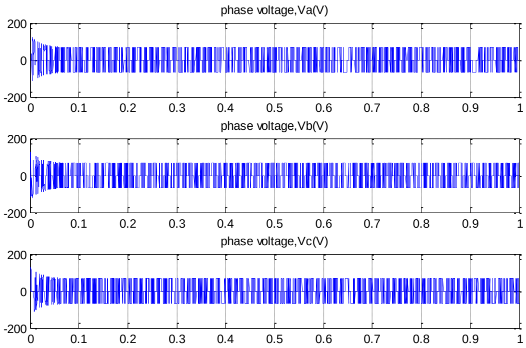


Fig.33.Simulation result of phase voltage for constant speed

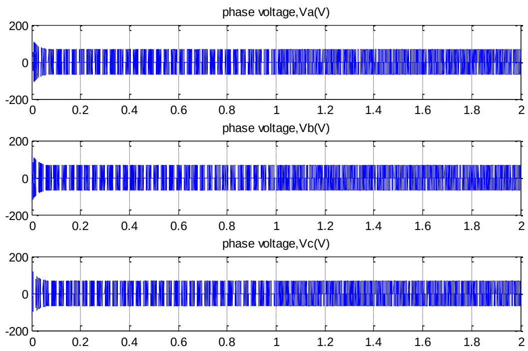


Fig.34.Simulation result of phase voltage for step change in speed

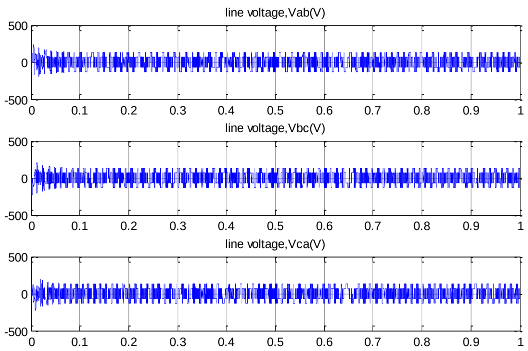


Fig.35. Simulation result of line voltage for constant speed

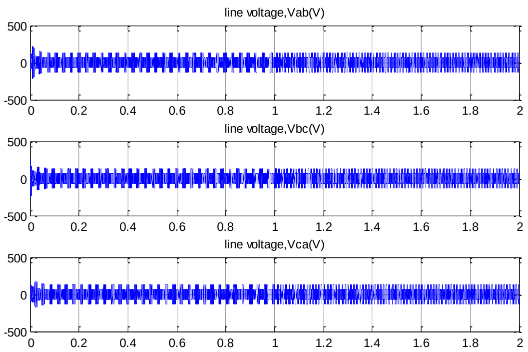


Fig.36.Simulation result of line voltage for step change in speed

5) Output of Current Block for a Constant and Step Change in Speed:

Phase ‘c’ current reaches the $I_{max}$ value before phase ‘b’ current goes to zero. As the result, the phase “a” current decreases and torque increases during the commutation period. Therefore it is noted that in the developed simulation model, the transient characteristics & steady-state conditions are well examined

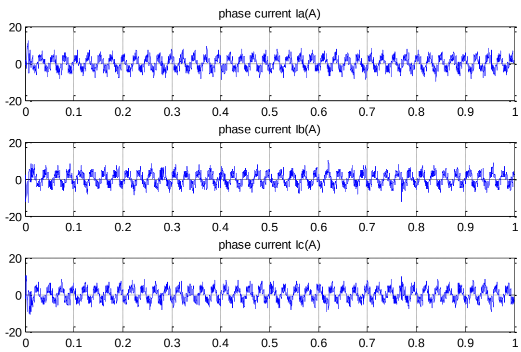


Fig.37.Simulation result of phase currentfor constant speed

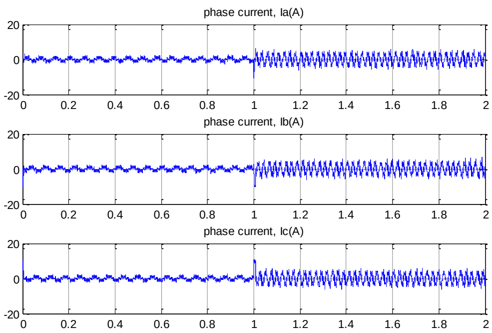


Fig.38.Simulation result of phase currentfor step change in speed

## V. CONCLUSION

Asimple, accurate and fast running Matlab / Simulink model for an entire PV fed three-phase star connected BLDC Motor drive is implemented. The trapezoidal back EMF waveform is modelled and operating speeds are calculated. With the help of PI controller, the real speed reaches the command value where the generated constant torque is taken as reference, the maximum current reference value ($I_{max}$) is calculated and utilized in the hysteresis control block. Using switching function concept voltage and current waveforms of the inverter is obtained. In the BLDC Motor drive, duty cycle controlled voltage pwm technique and hysteresis current control technique is used for obtaining the fast dynamic responses during transient states. Therefore, the mechanism of phase commutation and generation of torque ripple is observed and analysed. Thus the proposed model is used to predict the performance of drive during transient as well as steady state operation.

## REFERENCES

[1]. “Electric motor Drives – Modelling, Analysis and Control”, R.Krishnan, second edition, Pentice-Hall of India Private Limited, New Delhi.
[2]. Modern Power Electronics and Drives”, Bimal K.Bose,Prentice Hall PTR,2002.
[3]. Power Electronics – Circuits, Devices and Applications”Muhammed H. Rashid, Third edition,Pearson-Prentice hall.
[4]. Kusko and S.M.Peeran, “Definition of the brushless DC motor,” proc. Of the IEEE, Industry Application society annual meeting IAS’88,pp.20 – 22, 1988.
[5]. Kenjo and S. Nagamori, Permanent Magnet and Brushless DC Motors, Tokyo: Sogo Electronics, 1984.
[6]. P. Pillay and R. Krishnan, “Modeling, simulation, and analysis of permanent-magnet motor drives, part II: the brushless DC motor drive,” IEEE Trans. on Industry Applications, vol. 25, no. 2, pp. 274–279, March/April 1989.
[7]. R. Carlson, M. Lajoie-Mazenc, and C. dos S. Fagundes, “Analysis of torque ripple due to phase commutation in brushless DC machines,” IEEE Trans. on Industry Applications, vol. 28, no. 3, pp. 632–638, May/June 1992.
[8]. P.D.Evans and D.Brown, “Simulation of brushless Dc drives,”Proc. Of the IEEE,vol. 137, no.5, pp.299-308, September 1990.
[9]. E. P. Wiechmann, P. D. Ziogas, and V. R. Stefanovic, “Generalized functional model for three phase PWM inverter/rectifier converters,” Proc. of the IEEE Industry Application Society Annual Meeting IAS’85, pp. 984–993, 1985.
[10]. B. K. Lee and M. Ehsani, “A simplified functional model for 3-phase voltage-source inverter using switching function concept,” IEEE Trans. on Industrial Electronics.
[11]. Power Switching Converters- Simon Ang and Alejandro Oliva, second edition, Taylor and Francis, 2005.
[12]. DSP Based electro Mechanical Motion Control- Hamid A. Toliyat and Steven Campbell, CRC press LLC, 2004.
[13]. Fundamentals of Power Electronics- Robert W. Erickson and Dragan Maksimovic, second edition, Kluwer academic publisher, 2004