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Solar Power Geared BLDC Motor for EV Incorporating Modified SEPIC Converter

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ABSTRACT*:* This paper presents set of harnessing solar energy for electrical vehicle where BLDC machine is a sole heart of Electric Vehicle (EV). The solar Photo Voltaic (PV) array is modeled for study purpose. Requirement of huge voltage gain is fulfilled by a non-galvanic modified Single Ended Primary Inductor Converter (SEPIC). The conventional 3 phase H-bridge inverter (Voltage source Inverter (VSI) - SPWM drive based) is used in BLDC motor. Basic modeling of BLDC machine with few assumptions is used for entire experimentation to validate the analytical study. MATLAB based simulation is carried for a 2 HP BLDC machine system. The performances like Speed, Torque, Current, Voltage and Back emf of the system are analyzed , validated and resulting waveforms are confirming to battery equivalent system performances is given.

KEYWORDS: Solar PV, modified SEPIC, VSC, H-bridge BLDC, SPWM, EV

I. INTRODUCTION

As fossil fuels are getting exhausted and more over the electric power generation is highly polluting the atmosphere, the entire world focus on renewable energy sources in which harnessing of solar power using PV module is taken as the first step in this paper. Solar power is abundant in tropical countries like India. Moreover the solar panel is portable so its usage is unlimited and more suitable for some drugs (maintained at low level temperatures) has to be transported for long distances. The DC voltage gain of the PV modules can be increased by SEPIC converter but the gain is limited. To increase the voltage gain abruptly modified SEPIC converter with non-galvanic isolation is chosen in this paper. The increased DC voltage is inverted to AC by means of control logic circuits conventional. The stator armature windings of (BLDC) Brushless DC Motor makes easy to dissipate heat away from the windings. BLDC Motor finds wide range of applications from hard disk drives to hybrid electric vehicles owing to the following advantages over brushed DC motors viz.,

a) Higher speed ranges and efficiency.
b) Higher dynamic response & Power density
c) Better speed Vs. Torque characteristics
d) Noiseless with 4 quadrant operation and maintenance free.
e) Tenacious & low electromagnetic pollution
f) Regenerative braking.

It is otherwise known as (ECM) electronically commutated motor and having trapezoidal back emf waveforms and are fed with rectangular stator currents. To reduce the cost without compromising the performance is a tough task. Cost and circuit complexity are the important factors for design tradeoffs between technology and design hardware. The combined analysis of energy, environmental issues with respect to driver is a paradigm shift. Since the rotor has no winding they are not subjected to centrifugal forces. The rotor position is sensed by two methods

a) Hall sensor - temperature sensitive, reduce system reliability but suitable for low cost, low speed & low resolution.
b) Back emf- promising device widely used because reliable.

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Every commutation sequence has one of the windings energized positive, the second negative and the third left open. The hall sensor signal changes the state when the voltage polarity of back emf crosses from a positive to negative or from negative to positive. In ideal cases this happens on zero crossing of back emf but practically there will be a delay due to winding characteristics. Another important aspect is at very low speed the back emf is very low amplitude to detect zero crossing. The motor has to be started in open loop from standstill and when sufficient back emf is built to detect the zero crossing point, the control should be shifted to the back emf sensing. The minimum speed at which back emf can be sensed is calculated from the back emf constant of the motor.

II. MODELLING OF PV ARRAY

The equivalent circuit of SPV is shown in Fig. 1. The output P-V characteristics of cells are nonlinear as shown in Fig. 2. The solar PV output voltage is

$$V_{pv} = \frac{1}{\lambda} l_n \left[\frac{I_{sc} - I_p + I_0}{I_0}\right] - R_s I_{pv} \qquad (1)$$

Where

$$R_s = \frac{R_{SH} \times R_P}{R_{SH} + R_P}$$

$$I_{ph} = I_{PV} + I_D$$

$$I_{ph} = I_{PV}$$

I_{sc} is the cell short circuit current
I_o is the reverse saturation current
I_{PV} - PV Current
I_D- Ideal diode current (negligible)
R_s is the series cell resistance
λ is a constant coefficient (varies with the irradiation & temperature) and
V_{PV} - PV Voltage

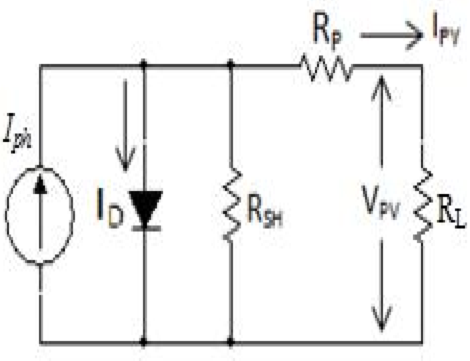

Fig.1. Equivalent circuit of PV solar cell.

To enhance more PV power (Ns) numbers of PV modules are connected in series and (Np) numbers of PV strings are connected in parallel in the PV array. The current rating and voltage rating of a PV array depends on 2 factors viz., irradiation and temperature levels. Equation (1) is calculated for different irradiation levels (G=600, 800, 1000 W/m^2) for the constant temperature, T=25^{0}C from the Ppv-Vpv characteristics of Fig. 2 as shown.

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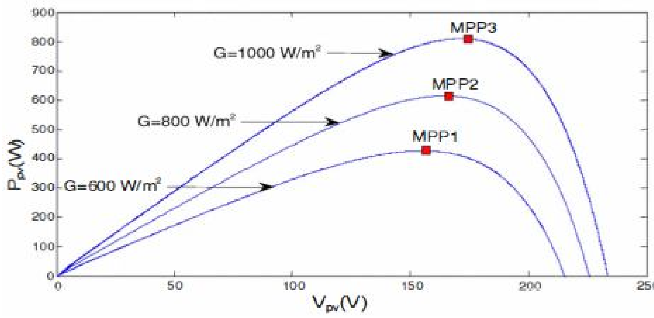

Fig. 2 P-V Characteristics of PV Module for different sun irradiations

From the above Fig. 2 P-V characteristics of PV module for different sun irradiations only one operating point is located on every Ppv-Vpv characteristics for which maximum PV solar power can be harnessed. This specific operating point for PV array is known as Maximum Power Point Tracking (MPPT) and identified by MPPT controller. For modeling of PV array the generalized equation of photovoltaic cell voltage is taken is to account and the output characteristics are also studied.

III. MODELLING OF BLDC MOTOR

For the simplified analysis and simulation purpose few assumptions are made in BLDC motor. The Assumption are

1. Three phase windings are symmetrical i.e., balanced system.
2. Magnetic saturation is neglected.
3. Hysteresis and eddy current losses are not considered.
4. Inherent resistances of each motor winding are R and self-inductances are L and they are considered as constant.
5. Stator winding are wye- connected hence zero sequence quantities are absent.

The Dynamic equivalent circuit of BLDC machine is shown in Fig. 3.

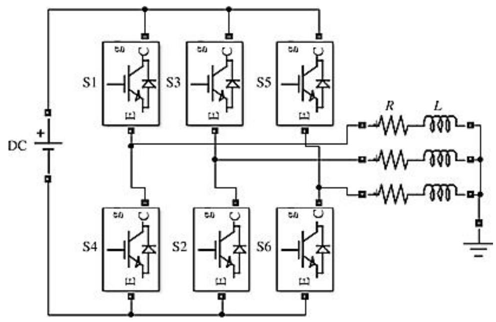

Fig. 3 Dynamic Equivalent circuit of BLDC Machine

BLDC motor is fed by a 3 phase voltage source. The source can be either sinusoidal or square wave, with the condition that the supply voltage should be less than the maximum voltage limit of the motor. The supply voltage pertaining to each phase of the winding can be written as

$$V_a = Ri_a + L\frac{di_a}{dt} + e_a \qquad (2)$$

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$$V_b = Ri_b + L\frac{di_b}{dt} + e_b \qquad (3)$$

$$V_c = Ri_c + L\frac{di_c}{dt} + e_c \qquad (4)$$

Where
L is armature self-inductance [H]
R is armature resistance [Ω]
V_a, V_b, V_c - terminal input voltage [v]
i_a,i_b,I_c - motor input current [A]
and e_a,e_b,e_c - motor back emf [v]

Where the back emf is function of rotor position with 120^0 phase angle difference hence

$$e_a = Kf(\emptyset)\omega \qquad (5)$$

$$e_b = Kf\left(\emptyset - 2\frac{\pi}{3}\right)\omega \qquad (6)$$

$$e_c = Kf\left(\emptyset + 2\frac{\pi}{3}\right)\omega \qquad (7)$$

where
k is back emf constant of one phase $\left[\frac{V}{Rad/sec}\right]$
Ø - electrical rotor angle[^{0}el]
ω - rotor speed [rad/s]
f - supply frequency

The relation between electrical rotor angle and mechanical rotor angle $\emptyset_m$ (rad) is

$$\emptyset = \frac{P}{2}\emptyset_m \qquad (8)$$

where
P – Number of rotor poles.

The total electrical torque 'Te'[Nm] developed at the output can be expressed as follows

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \qquad (9)$$

Similarly the equation of mechanical part is expressed as

$$T_e - T_l = \frac{Jd\omega}{dt} + B\omega \qquad (10)$$

where
T_l is load torque [Nm]
J inertia of rotor and coupled shaft [kg m^2]
B friction constant [N/rad]

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Hence for BLDC machine simulation and analysis purpose the above seen phase voltage, back emf and Torque equations are utilized.

IV. MODELLING OF MODIFIED SEPIC

SEPIC stands for ‘Single Ended Primary Inductance Converter’ in which the output DC voltage gain is more than conventional DC converters. To improve the voltage still higher, modified SEPIC converter is incorporated because losses and noise are reduced.

A. SEPIC Converter:

The circuit of SEPIC converter is shown in Fig.4. Its significant is nothing but switching voltage is equal to the sum of the input and output voltages.

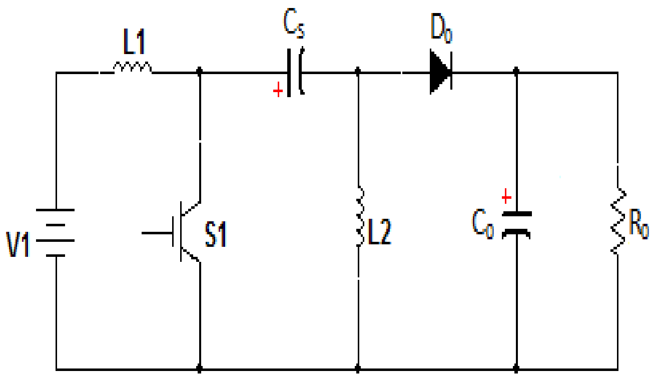

Fig. 4 Conventional SEPIC

B. Modified SEPIC Converter

The modification of the SEPIC converter is accomplished by adding two components, diode D_M and the capacitor C_M from SEPIC converter as shown in Fig. 5.

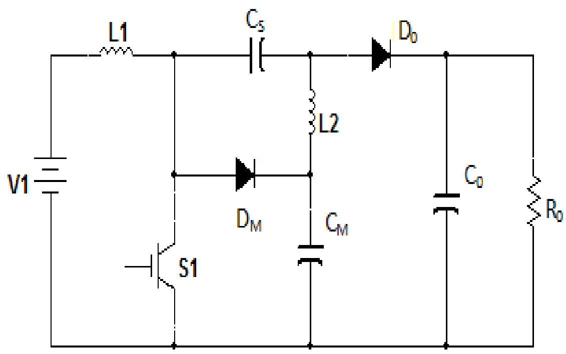

Fig. 5 Modified SEPIC without Magnetic coupling

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To improve the converter static gains some modifications are proposed. The capacitor c_m is charged with the output voltage the polarity of the capacitor c_s is reversed. The assumption made is capacitors are considered as a voltage source and the semiconductors are considered to be ideal. In the continuous conduction mode (CCM) it operates in 2 modes.

1) Mode-I [$t_0 – t_1$]:

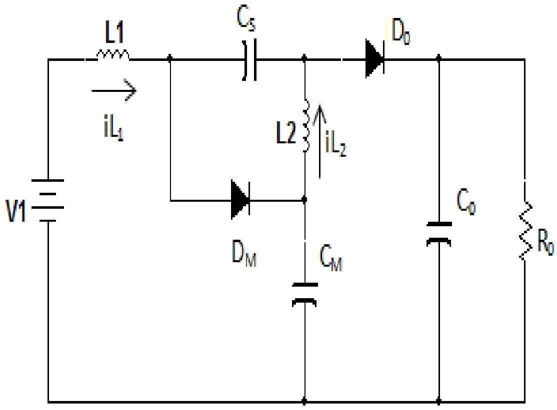

Fig. 6 Mode-I [$t_0 – t_1$]

The equivalent circuit of mode-I is shown in Fig. 6. Where switch S is turned off at t_o and the energy stored in the input inductor L_1 is transferred to the output through the capacitor $C_s$and output diode D_0 and further transferred to the capacitor C_m through the diode D_m. Hence switch voltage is equal to C_m capacitor voltage. The energy stored is the inductor L_2 is transferred to the output through the diode D_2.

2) Mode-II [t_1-t_2]:

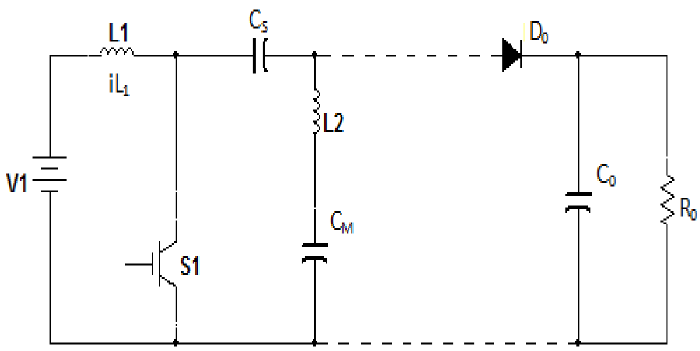

Fig. 7 Mode-II [$t_1 – t_2$]

The equivalent circuit of mode-II is shown in Fig. 7. Where switch S is turned on and the diodes D_m and D_0 are blocked at the instant t_1 and the inductors L_1 and L_2 store energy simultaneously. The input voltage is applied to the input inductor L_1 and the output voltage V_{cs} -V_{cm} is applied to the inductor L_2. The V_{cm} voltage is higher than the V_{cs} voltage. The maximum voltage in all diodes and in the power switch is equal to C_m Capacitor voltage. The output is equal to the sum of the voltage across capacitors C_s and C_m. The average L_1 inductor current is equal to the input current and the average L_2 inductor current is equal to the output current.

In CCM operation the static gain of the convertor at the steady state is

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$$\frac{V_o}{V_i} = \frac{1-D}{1+D} \qquad (11)$$

This gain (11) is higher than conventional converters. The maximum switch voltage is equal to the V_{cm} voltage (12) but switch voltage is lower than converter output voltage.

$$\frac{V_{cm}}{V_i} = \frac{1}{1-D} \qquad (12)$$

Similarly the voltage across capacitor C_s is (13)

$$\frac{V_{cs}}{V_i} = \frac{D}{1-D} \qquad (13)$$

Where D is duty cycle.

The static gain and capacitor voltages (V_{cm} & V_{cs}) operating in DCM (discontinuous mode) are represented in equation (14), (15) and (16) respectively.

$$\frac{V_o}{V_i} = 1 + \frac{V_i - D^2}{2 i_o Leq.f} \qquad (14)$$

$$\frac{V_{CM}}{V_i} = 1 + \frac{V_i - D^2}{4 i_o Leq.f} \qquad (15)$$

$$\frac{V_{cs}}{V_i} = \frac{V_i - D^2}{4 i_o Leq.f} \qquad (16)$$

$$Leq = \frac{L_1 L_2}{L_1 + L_2} \qquad (17)$$

C. Design aspect of the modified SEPIC converter

The converter is operating in CCM with the following details

- Output power, Po =1500W
- Input voltage, Vi =45V
- Output voltage, Vo =450 V
- Switching frequency, f =24 khz

1) Switch duty cycle: With reference to static gain the duty cycle is

$$D = \frac{V_o - V_i}{V_o + V_i} \qquad (18)$$

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2) *Switch and diode voltages:*The diode output voltage $V_{DO} = V_o - V_{CS}$. The switch voltage Vo= Voltage across the diode Dm

$$V_S = V_{DO} = V_{DM} = \frac{V_i}{1-D} \qquad (19)$$

3) *L_1 and L_2 inductance:* Assuming the current ripple$\Delta i_L = 5A$

$$L_1 = L_2 = \frac{V_i - D}{\Delta i_L - f} \qquad (20)$$

4) *Capacitor C_s and C_m:* Let the capacitor voltage ripple ∆Vc = 10% of the nominal voltage of C_m

$$C_S = C_M = \frac{I_o}{\Delta V_C \cdot f} \qquad (21)$$

where

$$\Delta V_c = \left[\frac{V_i}{1-D}\right]\frac{10}{100} \qquad (22)$$

5) *Semiconductor current effort:* The diode currents are equal to the output current

$$I_{DO} = I_{DM} = I_O = \frac{P_O}{V_O} \qquad (23)$$

V. SIMULATION

A) Solar PV Model

The solar PV Model is created using the foreseen equation (1)

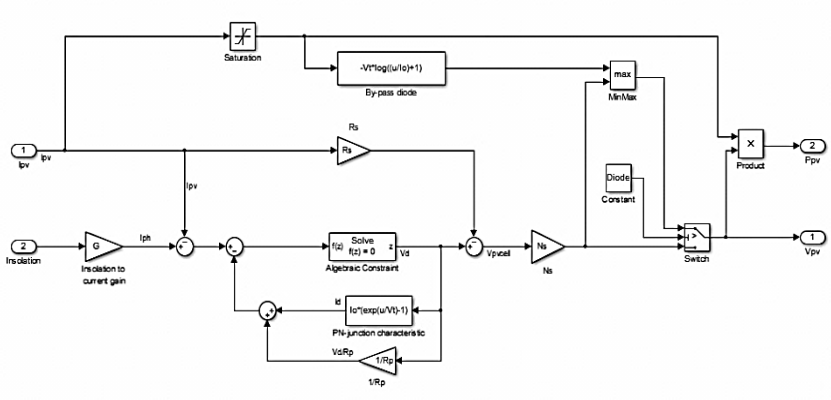

Fig.8 Solar PV Model

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B) Multiple SPV

To increase the voltage rating in a PV array ‘n_s’ number of modules can be connected in series and to increase current rating ‘n_p’ number of PV modules can be connected in parallel. In this paper parallel connection is preferred because voltage gain is taken care by SEPIC converter

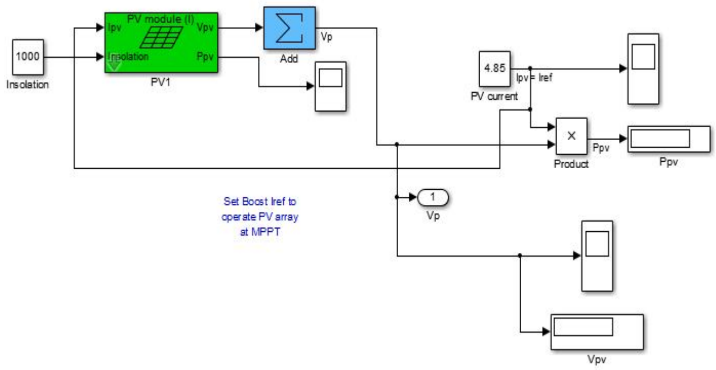

Fig. 9 Multiple SPV

C) Modified SEPIC Converter

The modified SEPIC converter is designed as per the Reference paper [2] and as shown in Fig.5. The component values are desired by the equations (11-23)

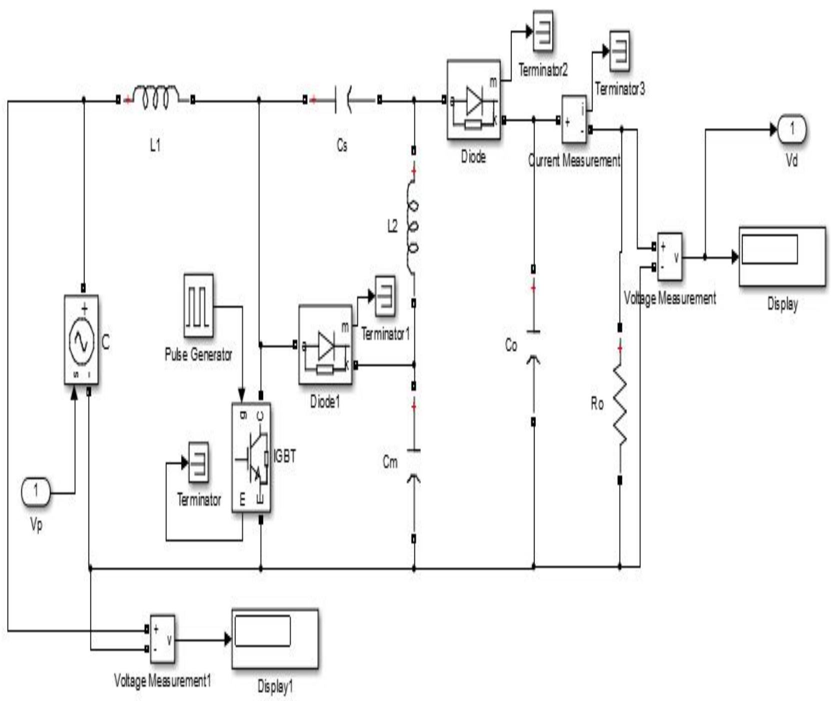

Fig. 10 Modified SEPIC converter

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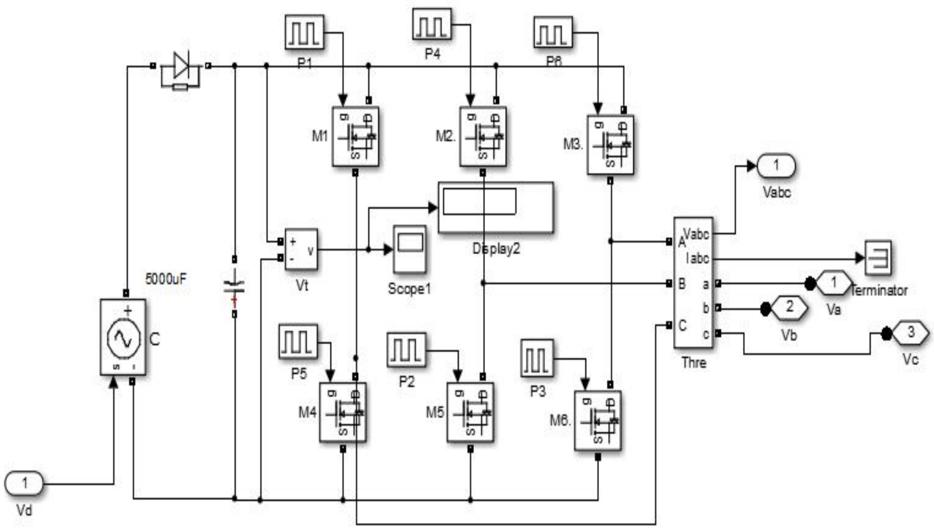
D) Inverter

The inverter used in this paper is conventional (VSI) voltage source inverter driven by simple sine PWM technique.



E) BLDC model

The supply voltage in Phase 'a' (V_a) vide equation (2), Phase 'b' (V_b) vide equation (3), Phase 'c' (V_c) vide equation (4), Electromagnetic Torque vide equation (9) and Motor Torque vide equation (10) are used in the proposed BLDC motor model.

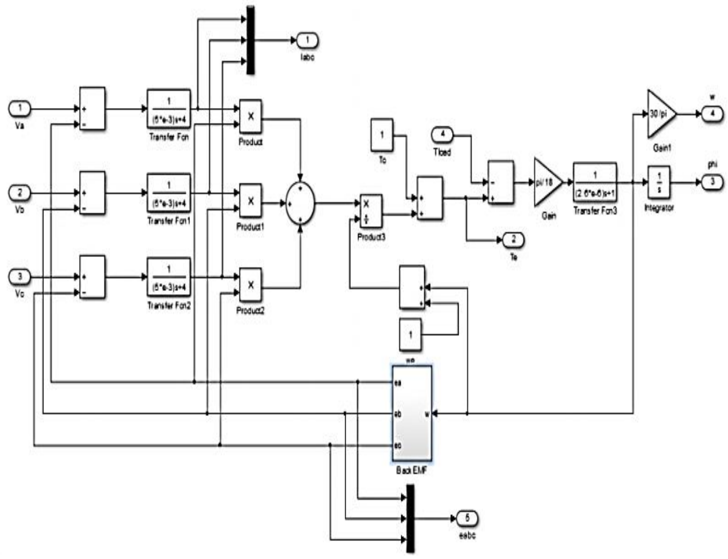


Fig. 12 BLDC model

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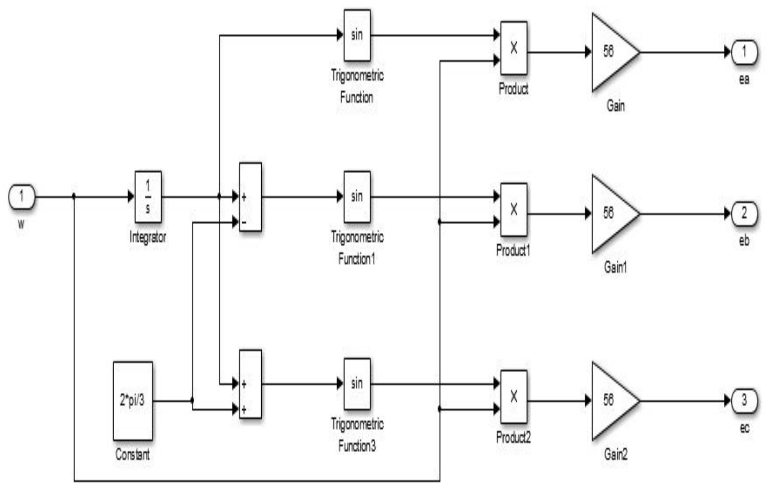
F) Back EMF

The sine back emf of Phase ‘a’ (e_a) vide equation (5) , Phase ‘b’ (e_b) vide equation (6) and Phase ‘c’ (e_c) vide equation (7)
are obtained from the back emf Simulink model



G) Complete Simulation Circuit

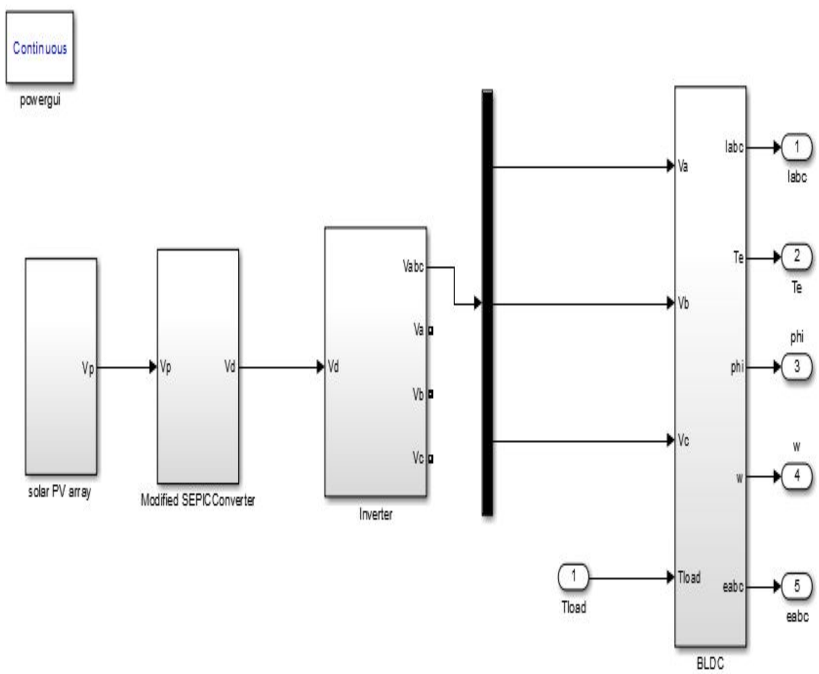


Fig. 14 Complete Simulation Circuit

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VI. RESULT ANALYSIS AND DISCUSSION

The figure shows the result for the following BLDC Drive Parameters with constant speed and Torque.

A. Solar Photovoltaic Array

Each solar cell produces 24V, 1.65A, two serially connected solar cell produced 48V,3.3A and 10 Parallely connected combination produce 48V, 33.3A

B. Modified SEPIC Converter

Output power P_o= 1500W, Input Voltage V_i = 45V, Output Voltage V_o=450V and the frequency is 24Khz.

1) Duty Ratio: $\left[D = \frac{T_{ON}}{T_{ON}+T_{OFF}}\right]$

$$D = \frac{V_o - V_i}{V_o + V_i} = \frac{450 - 45}{450 + 45} = 0.8182$$

2) Voltage across the Diodes:

$$V_S = V_{DO} = V_{DM} = \frac{V_i}{1 - D} = \frac{45}{1 - 0.8182} = 247.5V$$

3) Inductors:

$$L_1 = L_2 = \frac{V_i.D}{\Delta i_L.f_{sw}} = \frac{45 \times 0.8182}{5 \times 24 \times 10^3} = 3.06825 \times 10^{-4}H$$

For Ripple Current, Assum $\Delta i_L = 5A$

4) Capacitors:

$$C_S = C_M = \frac{I_O}{\Delta V_c.f} = \frac{3.33}{24.75 \times 24 \times 10^3} = 5.6\mu f$$

Change in Capacitor Voltage

$$\Delta V_C = \frac{V_i}{1 - D} \times \frac{10}{100} = \frac{45}{1 - D} \times 0.1 = 47.5 \times 0.1 = 24.75V$$

$$I_{DO} = I_{DM} = I_O = \frac{P_O}{V_O} = \frac{1500}{450} = 3.33A$$

C. Three Phase Full H-Bridge (VSI)

DC input voltage is 450V, AC Output Voltage 415V, I_O =2.3187A

D. BLDC machine

AC input Voltage =415V, Input current = 2.318A, Output Power= 1.5 KW

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VII. WAVEFORMS

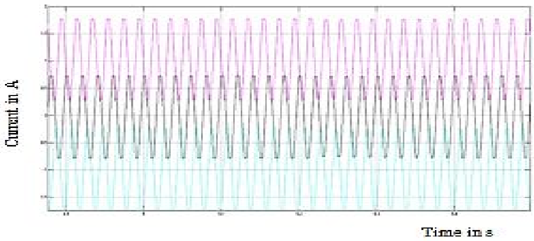

Fig. 15 Input current of BLDC machine

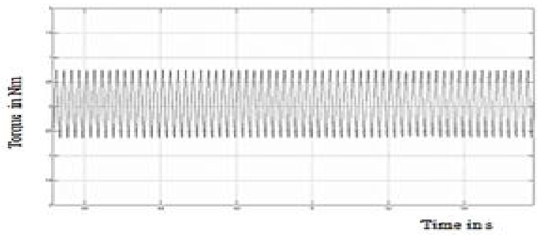

Fig. 16 Developed torque of BLDC machine

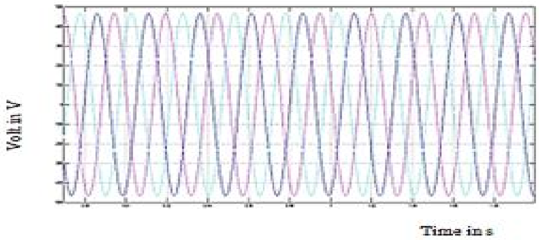

Fig. 17 Back EMF of BLDC machine

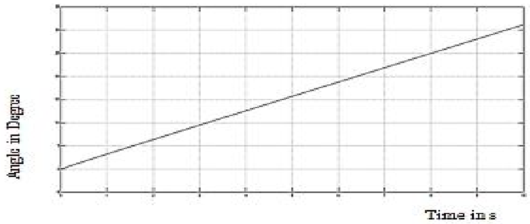

Fig. 18 Output phi of BLDC machine

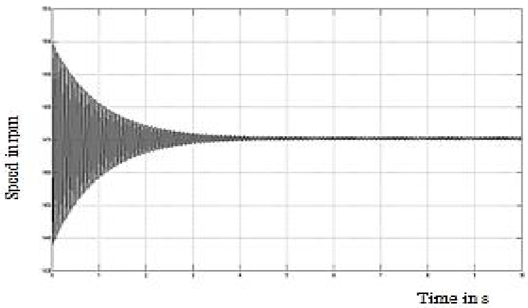

Fig. 19 Speed of BLDC machine

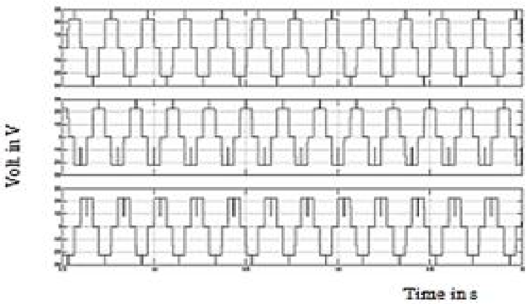

Fig.20 Output voltage of VSC

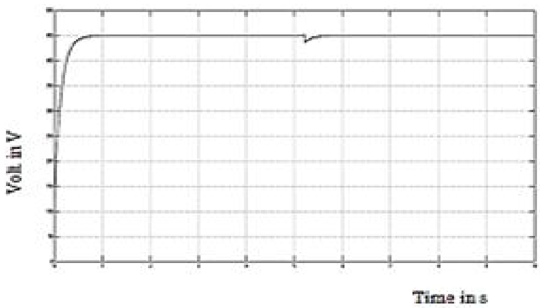

Fig. 21 Output voltage of Modified SEPIC converter

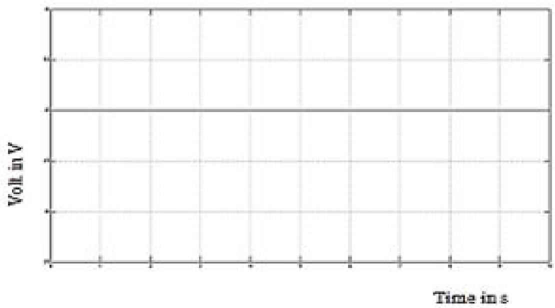

Fig. 22 Output voltage of solar PV

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VIII. CONCLUSION

The modelling presented in this paper for solar PV array and BLDC machine with sinusoidal back emf are much useful to carry research further in solar electric vehicle, open loop modified SEPIC converter fed, VSC implemented BLDC drive is designed and experimented in MATLAB platform to validate analytical results. To carry such a research a 2Hp BLDC machine is chosen as a test machine for that [ten (10) parallel (two PV cell connected in series)] Twenty PV cell with 24V and 1.65A is used as energy source. The 45V solar voltage is boosted to 450V DC by modified SEPIC converter, 450V DC is supplied to VSI fed BLDC machine. The performance curves are closely equivalent to that of the battery supplied Electric vehicle. In near future suitable control technique will be employed to the system for improving the performances and hardware implementation is also an another scope.

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