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Fuel Cell Supplied SVPWM Controlled Inverter Fed PMSM Drive in an Electrical Vehicle

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Abstract: **This paper presents fuel cell converter based supply system and SVPWM controlled inverter fed PMSM drive in an Electrical Vehicle. Fuel Cell Electric Vehicles (FCEV) has been typically gaining popularity in electrical vehicle technologies due to their eco friendly nature cleanness, high efficiency, and high reliability. These FCEV are "rechargeable energy storage system" (RESS) and they provides good acceleration and regenerative braking. While the output voltage of Fuel cell stack is very low so by providing proper closed loop boost converter then the FC converter system can be used as an eco friendly DC source in electrical vehicles and this closed loop control of boost converter is also used to maintain the converter output constant irrespective of the pressure levels in the fuel cell. In this paper PMSM drive is introduced in electrical vehicles to achieve high performance than induction motor like high speed, high torque and high efficiency. Gating signals are generated to the inverter by using SVPWM technique and the output of the inverter is fed to the PMSM drive through LC filter to reduce the ripples in inverter output.**

Keywords: Fuel cell system, DC-DC boost converter, Space vector power width modulation, permanent magnet synchronous motor, Speed control, electrical vehicles.

I. INTRODUCTION

Reducing dependency on fossil fuels is a major challenge for most of the automotive industries. Hence the development of eco friendly electrical vehicles has gaining popularity in recent years and fuel cell technologies are expected to become an attractive power source for automotive applications because of their cleanness, high efficiency, and high reliability. There are various fuel cells are available for use in electrical vehicles but for electrical vehicles PEMFC is the primary preference due to their high power density with lower operating temperatures when compared to other types of FC systems [2]. But the problem in PEMFC is output power is in the range from a few watts to several hundred kilowatts and the open circuit voltage of the single cell is in the range of 0.6-1.2V.To get higher operating voltage& power many such cells are stacked and connected in the form of cascaded, series & parallel connection. Even though Output voltage of the fuel cell system is always low when compared with the common DC bus voltage which fed to the inverter. Hence interfacing the Fuel Cell and the DC/DC converter is used to boost the fuel cell voltage and to regulate the DC-link voltage [3].

In EV important requirements for electrical drive are low weight, small volume, high efficiency and low cost. Presently IM is the obvious electrical drive alternative for electrical vehicles. PMSM drive can achieve high performance than induction motor like high speed, high torque and high efficiency. But the main problem in PMSM drive is torque ripples. If such a PMSM drive is used in the EV applications then it does not give satisfactory operation. So minimization of these ripples and wide speed range variation also necessary for PMSM drive. This can be achieved by proper tuning of PI controller [4] and inverter gate switching sequences are controlled by Space Vector Pulse Width Modulation (SVPWM) [5].

II.PROPOSED SYSTEM

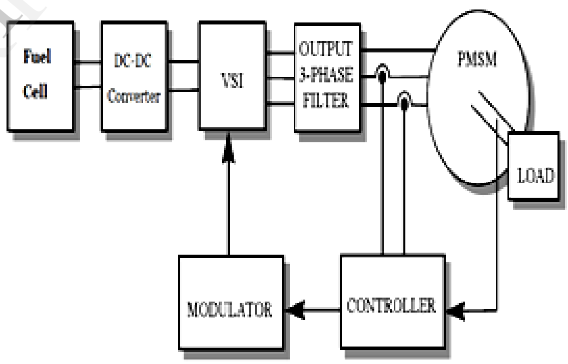

Fig1.Fuel cell converter supplied SVPWM controlled inverter fed PMSM drive in electrical vehicles

Fig1 shows the block diagram of fuel cell converter based supply system and SVPWM controlled two level inverter fed PMSM drive in EV. The output of the fuel cell is very low i.e. 0.6v to 0.7v. These fuel cells connected in such a manner to obtain the voltage up to 35v, this voltage fed to boost converter to step up the voltage up to 220v DC. To get the regulated output voltage the closed loop boost converter is preferred and PI controller is used as controller in feed back circuit. Some ripples occur in output due to power electronic switch in boost converter circuit. This rippled DC output is fed to the inverter as a source and gating signals required for the inverter is provided by SVPWM controller. The output AC voltage of inverter also having ripples due to power electronic switches in inverter so amount of ripple content increase. This AC output voltage is fed to the PMSM through LC filter to minimize the ripple contents. The speed of PMSM drive has taken as feed back and by comparing this speed with reference speed and error signal is generated. This error signal is taken as input to the PIcontroller and by proper tuning of PI controller voltage signals are generated and by proper modulation of voltages these signals are used in SVPWM signal formation.

II. MODELING OF PEM FUEL CELL SYSTEM

A fuel cell is a device that converts the chemical energy of a fuel and an oxidant directly into electricity. There are various fuel cells are available for use in electrical vehicles. But for electrical vehicles PEMFC is the primary preference due to their high power density with lower operating temperatures when compared to other types of FC systems. The basic schematic diagram of PEMFC is shown in fig.2

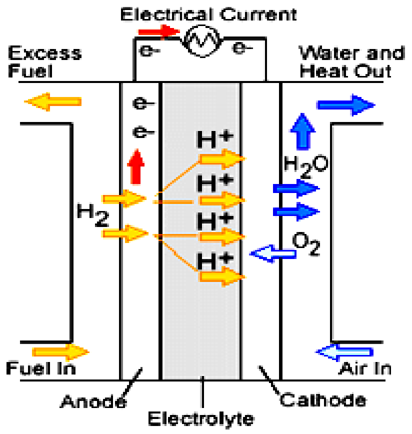

Fig2.schematic diagram of PEMFC

In PEM fuel cell electrochemical process starts on the anode side .At anode H_2 molecules are comes out from flow plate channels and anode catalyst divides hydrogen into H^+ and e^-Here H^+ passes through membranes and e^- travel to cathode over external electrical circuit. At the cathode hydrogen protons H^+ and electrons e^- combine with oxygen O_2 by use of catalyst, to form water H_2O and heat**.** Described reactions can be expressed using equations:

Anode side : $H_2 \rightarrow 2H^+ + 2e^-$ (1)

Cathode side**:** $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (2)

Overall reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (3)$$

To describe the static fuel cell voltage with respect current static model is the preferable. The static model of a fuel cell is modeled on the basis of the following empirical relationship

$$V_{fc} = E - V_{act} - V_{ohmic} - V_{conc} \quad (4)$$

Thermodynamic reversible potential (E):

The thermodynamic reversible potential is represented by the following nernest equation

$$E = E_0 - 0.85 * 10^{-3}(T - T_0) + [\frac{R}{2f}T(\log(PH_2) + \frac{1}{2}(\log(PO_2))] \quad (5)$$

Activation over voltage (V_{act}):

To start the chemical reaction certain proportion of energy is needed. This phenomenon produces a non-linear voltage drop called activation polarization. These losses occur on both anode and cathode. These losses describes by the tafel equation

$$V_{act} = \frac{RT}{\alpha Zf}\log\frac{I}{I_0} \quad (6)$$

Ohmic voltages (V_{ohmic}):

To flow electrons through the electrically conductive fuel cell components and to the flow of ions through the membrane causes a voltage drop, which can be expressed by Ohm's law:

$$V_{ohmic} = I(R_m + R_c) \quad (7)$$

Concentration over voltages (V_{conc}):

At the catalyst layers the consumption of reactant gases leads to concentration gradients and thus changes the partial pressure of the reactants, which affects the fuel cell voltage.

It describe by following equation

$$V_{conc} = -\frac{RT}{ZF}\log(1 - \frac{I}{I_{lim}}) \quad (8)$$

IV. FUEL CELL SUPPLIED BOOST CONVERTER

Converter which converts low level DC voltage to high level DC voltage called DC- DC Boost converter .DC/DC boost converters are best options for high step up and high switching frequency conditions. The switches are stressed on half of the total dc bus voltage. So low voltage rated switches are sufficient to obtain better switching and conduction performance. So efficiency and cost are better compare to conventional converters. It normally operates either in continuous conduction mode or in discontinuous conduction mode. In this paper boost converter operates in Continuous Conduction Mode (CCM) is shown in fig3

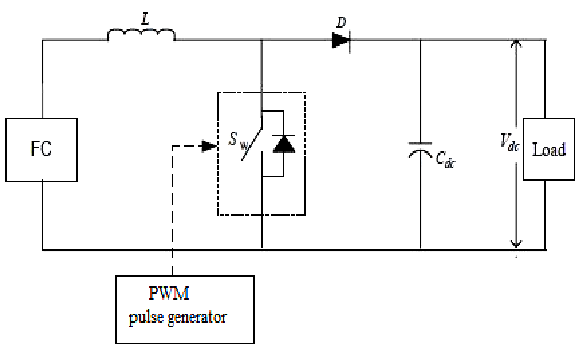

Fig3.Fuel cell supplied DC-DC Boost Converter Circuit Diagram

In this converter switching frequency is above 20 kHz so metal–oxide semiconductor field-effect transistors (MOSFET) is used as a switch. Switch is triggered by the pulse which is generated by PWM technique. Switch remains on during T_{on} cycle and off during T_{off} cycle so triggering is depends on the duty cycle. R is the resistor which is considering as a load .The selection of components like boost inductor value and capacitor value is very important to reduce the ripple generation for a given switching frequency.

CCM involves 2 step processes to get power transferred from source to load. Inductor stores the energy when the switch 'S' is turned ON, and its equivalent circuit is shown in figure4.Stored energy gets transferred to load through diode when the switch 'S' is turned OFF and its equivalent circuit is shown in figure5.

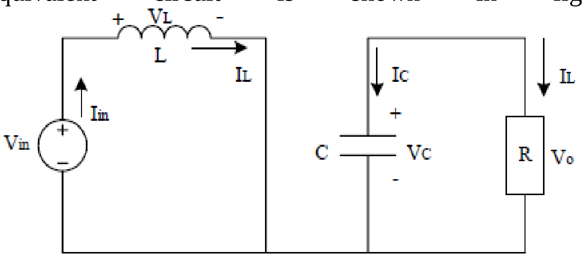

Fig4. DC/DC boost converter during switch on time.

Also equivalent waveforms of voltage across an inductor, current through diode, current through inductor, and capacitor current are shown in figure 6

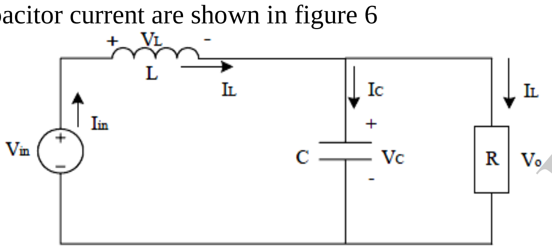

Fig5.DC/DC boost converter during switch off time.

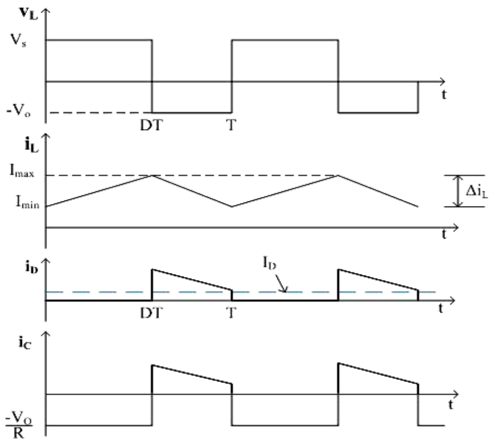

Fig6.Current and voltage waveforms of DC-DC Boost Converter

The relation between input voltage and load voltage for an ideal DC-DC Boost Converter, is given by

$$V_O = \frac{V_S}{(1-D)} \tag{9}$$

When boost converter is employed in open loop mode, it exhibits poor voltage regulation and unsatisfactory dynamic response. Hence, for output voltage regulation converter is generally provided with closed loop control. The block diagram of closed loop feedback dc-dc boost converter is shown in figure7.

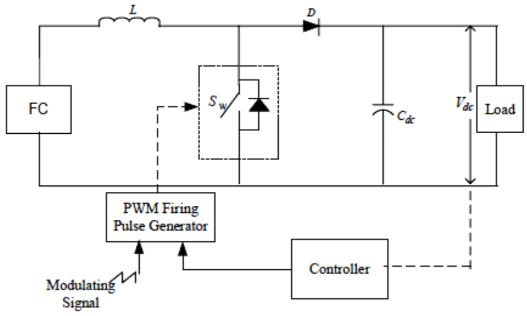

Fig7.DC-DC boost converter with feedback control.

The main advantages of the closed loop boost converter are, it converts the unregulated voltage into desired regulated voltage by varying the duty cycle at high switching frequency lowering the size and cost of energy storage components and higher efficiency & reduced component count.

V. SVPWM CONTROLLED VSI

Schematic drawing of a two level inverter is shown in Fig8. There are six switches in inverter. Where S1, S3 and S5 switches stand for upper switches while S2, S4 and S6 switches are down switches. Gating signals are provided by SVPWM technique. Three-phase output voltage waveforms are generated by various switching combination of the switches.

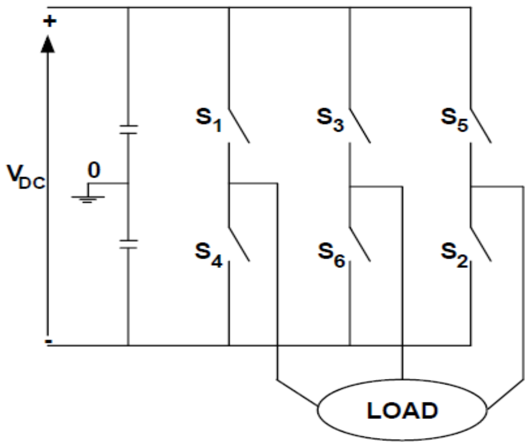

Fig8. Two-level inverter

There is various pulse width modulation techniques have been developed to generate gating signals for inverter. These PWM techniques control the total harmonic distortion of output voltage and also control the load currents. The most popular PWM technique for inverter is Sinusoidal PWM (SPWM) technique .But in SPWM it is difficult to change the sampling of sinusoidal waveform for digital application. For this reason, space vector PWM (SVPWM) technique is recently showing popularity for inverter applications.

SPACE VECTOR PWM (SVPWM):

Two level inverter Switching states are shown in fig9. In two level inverter there are $8(2^3)$ possible states. (000) and (111) are zero state vectors and reaming all are active state vectors. Hence in two level inverter space vector diagram is divide into six sectors.(sector-A,B,C,D,E,F) and space vector diagram of two level inverter is shown in fig10.

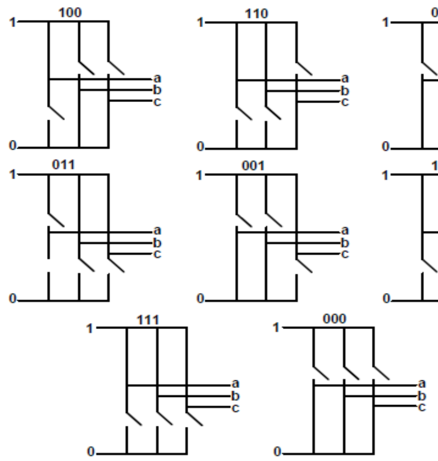

Fig9. Two level inverter Switching states

While implementing the SVPWM for two-level inverters can following steps are consider:

- Sector identification,
- Calculate the switching times, T1, T2, T0
- Find the switching states

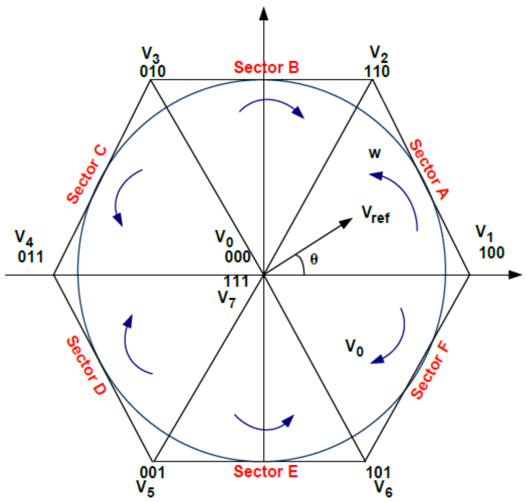

Fig10.Space vector diagram of two-level inverter

A three-phase-voltage vector and angle can be expressed as;

$$V_{ref} = V_d + V_q = \frac{2}{3}(V_{an} + V_{bn} e^{j\frac{2\pi}{s}} + V_{cn} e^{-j\frac{2\pi}{s}})$$

$$\theta = Tan^{-1}(\frac{V_q}{V_d}) \qquad (10\&11)$$

Where, V_{an}, V_{bn} and V_{cn} are three phase voltages and V_{ref} rotates at angular speed of w = 2.π.f.

a) *Sector identification:*

According to θ sector can be determined

Table1: Sector determination

Angle (θ)	Sector where V_{ref} placed
$0^0 \le \theta < 60^0$	Sector A
$60^0 \le \theta < 120^0$	Sector B
$120^0 \le \theta < 180^0$	Sector C
$180^0 \le \theta < 240^0$	Sector D
$240^0 \le \theta < 300^0$	Sector E
$300^0 \le \theta < 360^0$	Sector F

b) *Calculate the switching times:*

Vref is calculated by using two active voltage vector and one zero voltage vector. If Vref is located in Sector A, Vref is synthesized by V1, V2 and V0. According to this approach T1, T2 and T0 can be calculated as;

$$T_1 = \frac{\sqrt{3}}{V_{dc}} V_{ref} T_s Sin(\frac{\pi}{3} - \theta) \qquad (12)$$

$$T_2 = \frac{\sqrt{3}}{V_{dc}} V_{ref} T_s Sin(\frac{\pi}{3}) \qquad (13)$$

$$T_0 = T_s - T_1 - T_2 \qquad (14)$$

If T1, T2 and T0 switching times for all sectors can be generalized, they can be calculated by;

$$T_k = \frac{\sqrt{3}}{V_{dc}} V_{ref} \frac{T_s}{2} Sin(\frac{\pi}{3} - \theta + \frac{k-1}{3}\pi) \qquad (15)$$

$$T_{k+1} = \frac{\sqrt{3}}{V_{dc}} V_{ref} \frac{T_s}{2} Sin(\theta - \frac{k-1}{3}\pi) \qquad (16)$$

c) *Finding Switching States:*

Switching states for Sector A has been shown in Figure 11.

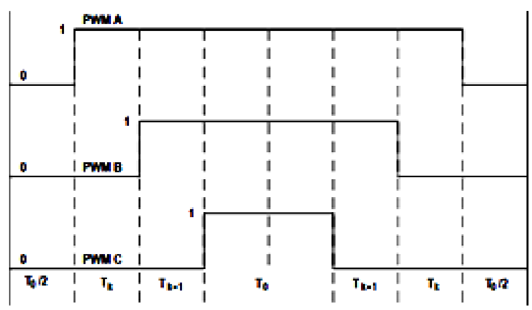

Fig11. Switching states for Sector A

Table2: switching states for two level inverter

Sectors	*Switching states*
Sector A	$V_0,V_1,V_2,V_7,V_7,V_2,V_1,V_0$
Sector B	$V_0,V_3,V_2,V_7,V_7,V_2,V_3,V_0$
Sector C	$V_0,V_3,V_4,V_7,V_7,V_4,V_3,V_0$
Sector D	$V_0,V_5,V_4,V_7,V_7,V_4,V_5,V_0$
Sector E	$V_0,V_5,V_6,V_7,V_7,V_6,V_5,V_0$
Sector F	$V_0,V_1,V_6,V_7,V_7,V_6,V_1,V_0$

Switching control signals produced by the SVPWM technique has applied to the inverter. Compare to the conventional SPWM inverter, SVPWM inverter is used to offer 15% increase in DC link utilization and low output harmonic distortions.

VI.CONTROL STRATEGY OF PMSM DRIVE

The control system of Permanent magnet synchronous motor mainly consists of two parts, the main drive circuit and the control circuit. The main drive circuit topology remains basically unchanged, while the study of the control system focuses on the control circuit and control strategies. The v/f control strategy of PMSM drive is shown in fig12.

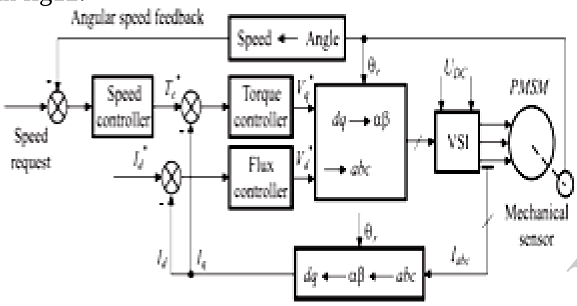

Fig12.V/F control strategy of PMSM drive

The speed of PMSM drive has taken as feed back and by comparing this speed with reference speed error signal is generated .This error signal is taken as input to the PI controller and by proper tuning of PI controller voltage signals are generated and by proper modulation of voltages these signals are used in SVPWM signal formation. The main advantage of this method is angular speed can be estimated indirectly from the frequency of the supply voltage i.e. no sensors are needed. So cost is optimal one. The angular speed calculated from the supply voltage frequency ac- cording to can be considered as the value of the rotor angular speed if the external load torque is not higher than the breakdown torque

VII.SIMULATION MODELS OF PROPOSED SYSTEM

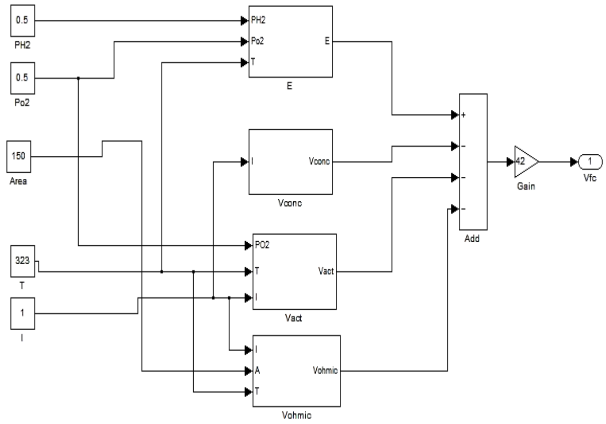

Fig.13 (a) Static model of PEMFC

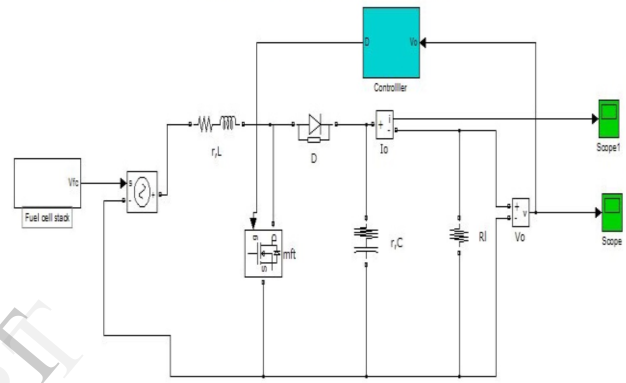

Fig.13 (b) Fuel cell supplied boost converter

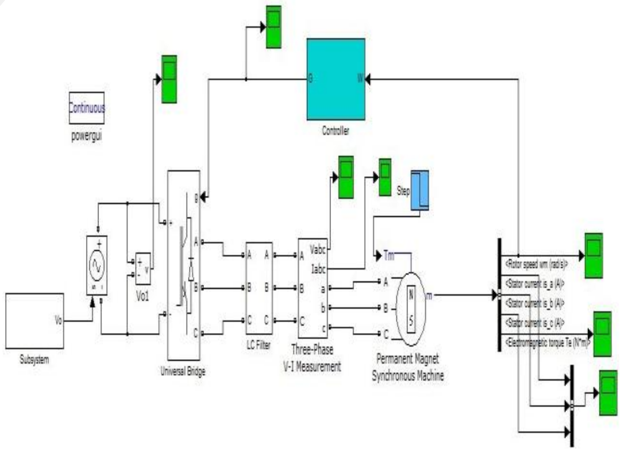

Fig.13(c) FC converter supplied SVPWM controlled inverter fed PMSM drive

VIII.SIMULATION RESULTS

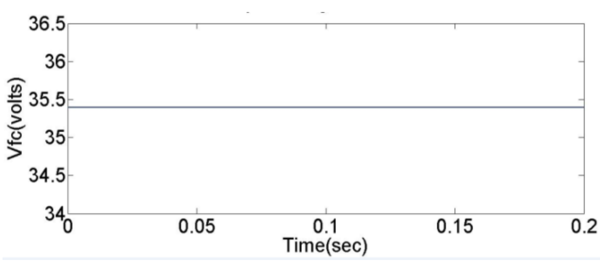

Fig.14 (a).Output voltage of fuel cell stack

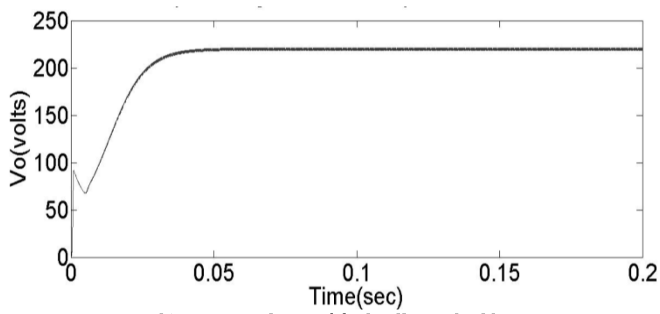

Fig.14 (b) Output voltage of fuel cell supplied boost converter

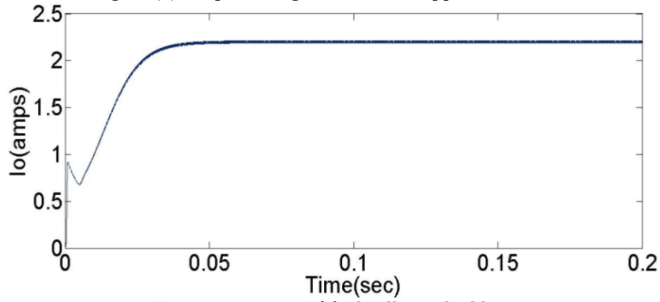

Fig.14(c) Output current of fuel cell supplied boost converter

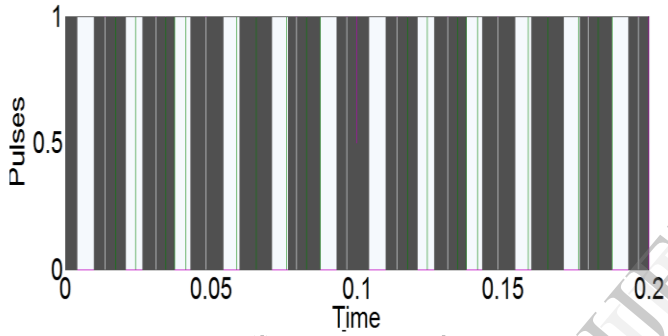

Fig. 14(d) SVPWM gating pulses

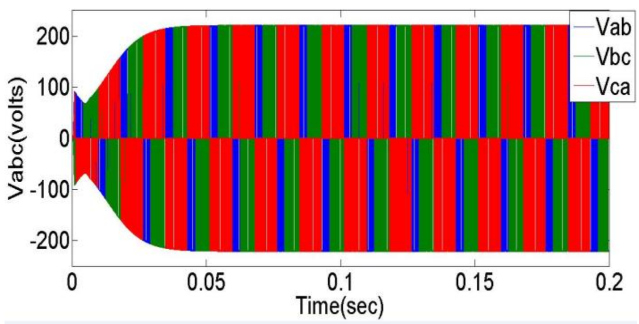

Fig. 14(e) output voltage of SVPWM controlled
Two level inverter

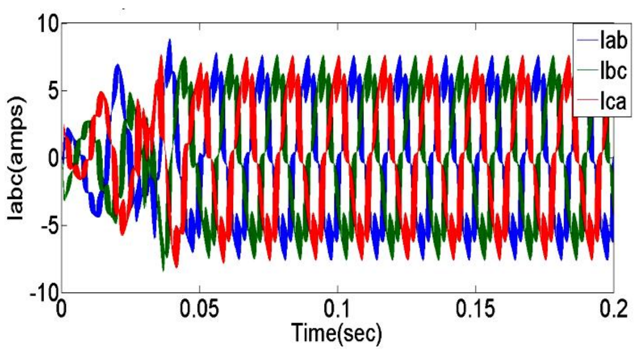

Fig. 14(f) output current of SVPWM controlled

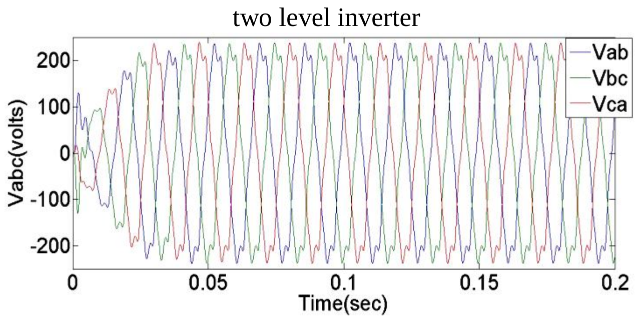

Fig 14(g)output voltage of SVPWM controlled two level inverter with filter

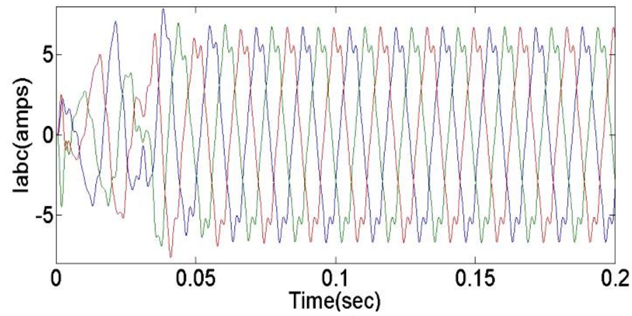

Fig. 14(h) Output current of SVPWM controlled
Two level inverter with filter

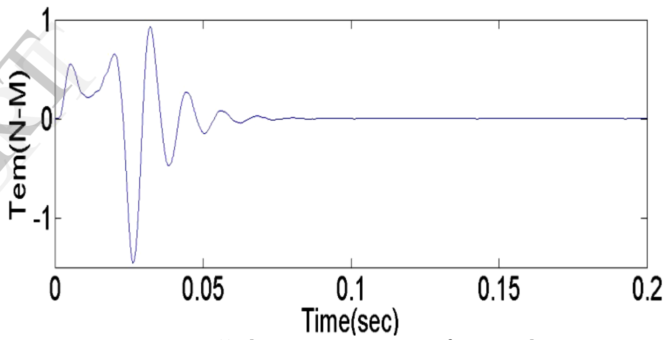

Fig.14 (i) electomagnetic torque of PMSM drive

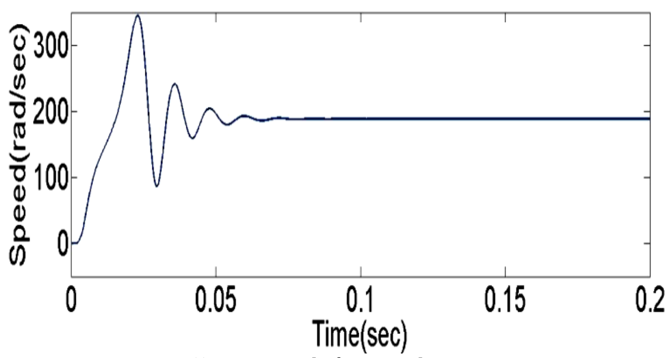

Fig .14(j) Rotor speed of PMSM drive

CONCLUSION

By providing proper closed loop boost converter then the FC converter system can be used as an eco friendly DC source in different DC source applications. During transient and instantaneous peak power demands of electric vehicle (EV) FC are recover energy through regenerative braking because of converter system so it can be used as rechargeable energy storage system. After minimization of Torque ripples PMSM drive can be used in wide speed range application so it is the one of the best alternative for IM drive. An auxiliary energy storage device such as a battery or super capacitor are installing in supporting with the FC then Same proposed system can be used in Hybrid electrical vehicles and power trains also.

APPENDIX

$\propto$=Charge transfer coefficient
R = universal gas constant,
F=faraday constant
I= fuel cell current density (A/cm^2)
I_o = exchange current density (A/cm^2)
R_m=membranes resistance (ohms),
R_C =conductive resistance (ohms)
n = number of electrons transferred per mole

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