

Speed Control of Fuel Cell Driven PMSM using Sliding Mode Control Based IDDB Converter

J.S.V.Siva Kumar, P.Mallikarjuna Rao



Abstract: *The concern over greenhouse gas emissions and their relation to global warming is one of the main reasons for the introduction of electric vehicles into the market. This paper discusses the design and simulation of the fuel cell-based electric vehicle. These FCEVs are "Rechargeable Energy Storage System" (RESS) and provide better acceleration along with regenerative braking as well. The output voltage of the fuel cell's stack is significantly low, then expanded by using the sliding mode control Interleaved Double Boost converter. The boost converter's increased output is given to the inverter to get AC to run PMSM. Using the Space Vector PWM process, gating pulses are given to the inverter and the inverter output is provided to the PMSM drive through the LC filter to minimize ripples in the inverter output. Simulation approaches use MATLAB / Simulink to determine the results*

Keywords : Fuel cell system, IDDB converter, Sliding Mode control, SPVPWM, PMSM, electrical vehicles.

I. INTRODUCTION

Transportation accounts for almost 40% of all greenhouse gas (GHG) emissions. The move to cleaner Fuel Cell Electric Vehicles (FCEVs) would bring significant benefits to our cities from air quality and climate. Such hydrogen-fuelled vehicles contain 30 to 60% less GHG emissions than conventional cars and do not emit toxic air pollutants. FCEVs are much cleaner than cars powered by gasoline and diesel. Smog and GHG emissions are created when gasoline or diesel fuel is burned in a car or truck. FCEVs are a "zero-emission vehicle," ensuring that no tailpipe emissions of harmful air pollutants or GHGs are produced. Now, FCEVs achieve slightly lower air emissions cuts than pure electric battery vehicles. Due to their important characteristics, PEMFC is given priority for use in electric vehicles compared to all forms of FC systems laterally with operating temperatures at lower levels [1]-[7]. The output Power developed is of any watts to approximately hundred kilowatts and the open circuit becomes an obstacle due to PEMFC.

The voltage output in the single cell is almost 0.8V to 1.2V. These cells are connected in series / parallel to obtain high voltage and power. Furthermore, these sources often vary considerably with changes in load.

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As a consequence, to raise the voltage and protect the fuel cell system from load variability, a step-up DC-DC converter must be connected between the fuel cell and the DC bus. In some cases, there is a need for a higher voltage gain so the traditional boost converter is not enough. In particular, Many researchers focus on a non-isolated topology with a higher voltage gain called the IDDB converter[8],[9].

Sliding mode control has been commonly used in linear and nonlinear systems with uncertainties and disturbances due to its decoupling and disturbance rejection features.

For the EVs, more efficiency, low volume, lower weight, and low cost are the conditions needed for an electrical drive. Now a days a PMSM drive with higher performance compared to AC motors such as high speed, torque and efficiency values [10]-[12]. PMSM drive's main drawback is the ripples in the torque. It won't give any significant operation because of these ripples. Better speed control is achieved, ripples are also minimized and gating pulses are also generated by the Space Vector Pulse Width Modulation for the inverter switches.

This paper is structured as follows: Fuel cell modeling, the next section focuses on the average modeling of IDDB converter with sliding mode controller and PMSM operated by SVPWM and it is tested under no load and different load conditions such as step, repeated step and ramp load. The conclusions are finally given.

II. PROPOSED SYSTEM

Figure 1 displays the block diagram of fuel cell-based electric vehicle. It includes a fuel cell, a DC-DC boost converter, a VSI fed PMSM powered by SVPWM. Single fuel cell's output voltage is almost 0.8V to 1.2V. For high operating voltages, it is therefore appropriate to combine number of cells in series / parallel. In this paper, the output of the fuel cell stack is almost 60V and this is increased to nearly 500V DC by using the sliding mode controller [10] controlled IDDB converter to get controlled output.

Suggested to achieve high operating voltage in this paper IDDB converter with closed loop operation, sliding mode controller is used as controller in feedback circuit. In this paper IDDB [8],[9]converter output is almost 500V which is input to Inverter to convert this DC to AC voltage. By connecting PMSM via LC filter, the ripples in AC voltage are minimized and the gating pulses for the inverter switches are generated using the space vector pulse width modulation[3],[4].

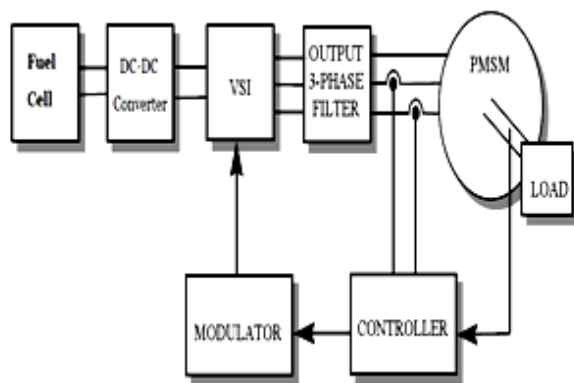


Fig. 1. PMSM Drive based on fuel cells

III. MODELLING OF THE FUEL CELL SYSTEM

Fuel cell is a device that is usually used to convert to electrical energy the chemical form of energy. We can normally use different types of fuel cells in electric vehicles, but PEM fuel cells are more critical because of their high-power density temperature operation. The clear diagram of PEMFC is shown in fig.2

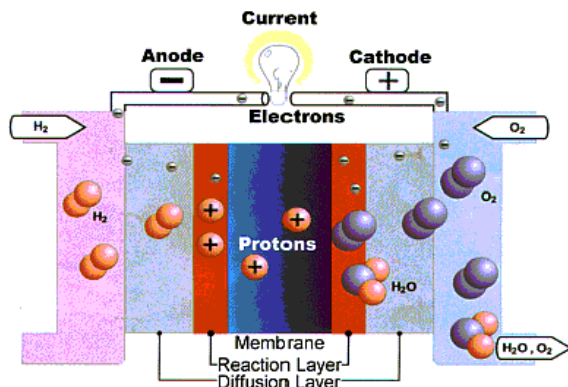
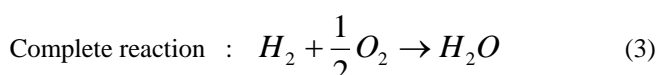
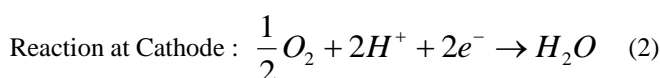
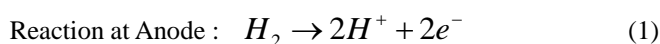


Fig. 2 PEM Fuel Cell

The proton conducting solid PEM is the nucleus of the cell. It is surrounded by two plates, a diffusion layer and a layer of reaction. The hydrogen diffuses through the anode and the diffusion layer up to the platinum catalyst, the reaction surface, under constant supply of hydrogen and oxygen. The reason for the current of diffusion is the tendency of oxygen reaction to hydrogen. In the fuel cell there are two main electrochemical reactions. One at the anode, and one at the cathode. At the anode, the reaction releases hydrogen ions and electrons that are critical for the production of energy. On its way to the cathode, the hydrogen ion travels through the polymer membrane, while an external loop is the only possible way for the electrons. The hydrogen ions react to water together with the outer electrical circuit electrons and the oxygen that has spread through the porous cathode.



The output voltage developed at fuel cell is quantified by using Ohms law and Nernst's equation.

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

Where E is Thermodynamic reversible potential

V_{act} is activation over voltage

V_{ohmic} is Ohmic voltages (V_{ohmic})

V_{conc} is Concentration over voltages

And all these values are measured by using below formulas

$$E = E_0 - 0.85 \times 10^{-3} (T - T_0) + \frac{RT}{2F} T \left[\ln(PH_2) + \frac{1}{2} \ln(PO_2) \right] \quad (5)$$

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

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

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

IV. FUEL CELL SUPPLIED SLIDING MODE CONTROL OF IDDB CONVERTER

IDDB converter's voltage gain is much higher than the typical boost. At a duty cycle of about 0.9, there is a maximum value for the actual condition, unlike the ideal condition that the output voltage increases with the duty cycle predictably. When the work cycle reaches the constraint, the voltage gain decreases rapidly as the loss of energy in that case is very significant.

The two-phase IDDB will be shown in Fig. 3, where the load is represented by ' R_o '. Each phase consists of a traditional inducer boost module and its corresponding pair of switches. Phase 1 and C_1 capacitor are referred to here as "Module 1" and vice versa.

A reduced-order design is introduced because the process is too difficult to examine. Given the symmetry of the system the parameters of each phase are expected to be the same and the voltage reference of the capacitor and the current reference of the inductor from the control point of view should also be the same. The variable δ is the duty cycle and it is also identical to both the modules.

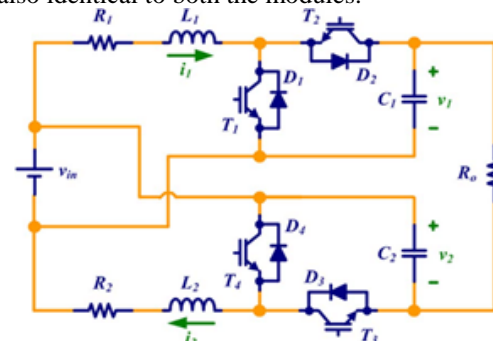


Fig. 3. IDDB With TWO phases.

As pointed out, this topology allows for more than two phases of modular design. To achieve symmetry, it is preferred to have even multiple phases. The aim of this section is to generalize the N-phase modeling of the converter topology.

The combination of the phases connected to the C_1 capacitor and the C_2 capacitor itself forms module-1 and module-2 vice versa. Figure 4 indicates the six-phase converter

The source current is given by:

$$i_{in} = i_1 + i_2 + i_3 + \dots + i_N - i_0 \quad (9)$$

Here are selected the 'N' inductor currents and two capacitor voltages are state variables and total N+2 state variables for N-phase IDDB.

The current differential equation in each module 1 inductor is given by

$$\frac{d}{dt} I_k = \frac{1}{L_k} (-R_k I_k - V_1 \bar{\delta}_k + V_{in}) \quad (10)$$

for $k=1, \dots, N/2$. Similarly for $k=(N/2)+1$ to N

The differential equation for the voltage in C_1 is given by

$$\frac{d}{dt} V_1 = \frac{1}{C_1} \left[\left(\sum_{k=1}^N I_k \bar{\delta}_k \right) + \left(\frac{-V_1 - V_2 + V_{in}}{R_0} \right) \right] \quad (11)$$

Similarly for voltage across C_2 Now, by exploring the symmetry of the system the same as two phases, all inductances and capacitors are the same and the current reference for each module is the same in each phase.

$$i.e., I_1 = I_2 = \dots = I_N = I$$

And for all phases the duty cycle is the same,

$$i.e., \delta_1 = \delta_2 = \dots = \delta_N = \delta$$

$$\text{Then } \frac{d}{dt} I = \frac{1}{L} (-RI - V\bar{\delta} + V_{in}) \quad (12)$$

$$\text{and } \frac{d}{dt} V = \frac{1}{C} \left[\left(\frac{N\bar{\delta}I}{2} \right) + \frac{-2V + V_{in}}{R_0} \right] \quad (13)$$

The state vector X is defined given below

$$X = [I \ V]^T \quad (14)$$

while the matrix of the system and input are

$$A = \begin{bmatrix} \frac{-R}{L} & \frac{-\bar{\delta}}{L} \\ \frac{N\bar{\delta}}{2C} & \frac{-2}{R_0 C} \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{L} \\ \frac{1}{R_0 C} \end{bmatrix} \quad (15)$$

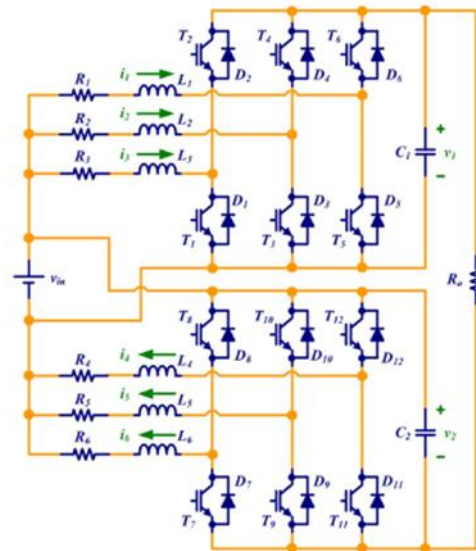


Fig. 4. Six phase IDDB converter

A. Small signal model

The converter's set of achievable equilibrium points is given by

$$X_{eq} = -A^{-1} B U. \quad (16)$$

Using above, The equilibrium points set can be written as

$$X_{eq} = \begin{bmatrix} I_{eq} \\ V_{eq} \end{bmatrix} = \begin{bmatrix} \frac{2 + 2\delta}{4R + NR_0(1-\delta)^2} \\ \frac{2R + NR_0(1-\delta)}{4R + NR_0(1-\delta)^2} \end{bmatrix} \quad (17)$$

Use the average method of state-space and assume the approximation of small signals The equivalent system near the point of equilibrium is given by

$$\dot{\tilde{x}} = A\tilde{x} + [(A_1 - A_2)X + (B_1 - B_2)U]\tilde{\delta} \quad (18)$$

Where A_1 and A_2 are the matrices when δ value for 1 and 0 respectively

X means The value of X at Equilibrium point

Using above values the equation can be simplified in to

$$\dot{\tilde{x}} = A\tilde{x} + [(A_1 - A_2)X]\tilde{\delta}. \quad (19)$$

Substituting all the above values finally

$$\dot{\tilde{x}} = \begin{bmatrix} \tilde{i} \\ \tilde{v} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} \tilde{i} - \frac{\bar{\delta}}{L} \tilde{v} + \frac{V_{in}}{L} \left\{ \frac{2R + NR_0(1-\delta)}{4R + NR_0(1-\delta)^2} \right\} \tilde{\delta} \\ \frac{N\bar{\delta}}{2C} \tilde{i} - \frac{2}{R_0 C} \tilde{v} - \frac{NV_{in}}{2C} \left\{ \frac{(2+2\delta)}{4R + NR_0(1-\delta)^2} \right\} \tilde{\delta} \end{bmatrix} \quad (20)$$

B. Methodology of Sliding Mode Controller

With reference inductor currents produced by means of small signal analysis, a feedback controller should be designed to direct the currents to the reference point. A sliding mode controller is designed as a broad signal model resulting in global stability due to the fast and robustness requirement of the converter output. A surface that slides is described by

$$\text{From this } S = \tilde{v} + k\tilde{i}$$

$$\dot{S} = \dot{\tilde{v}} + k\dot{\tilde{i}}$$

$$\begin{aligned} \dot{S} = & \frac{N\bar{\delta}}{2C} \tilde{i} - \frac{2}{R_0 C} \tilde{v} - \frac{NV_{in}}{2C} \left\{ \frac{(2+2\delta)}{4R + NR_0(1-\delta)^2} \right\} \tilde{\delta} \\ & + k \left[\frac{-R}{L} \tilde{i} - \frac{\bar{\delta}}{L} \tilde{v} + \frac{V_{in}}{L} \left\{ \frac{2R + NR_0(1-\delta)}{4R + NR_0(1-\delta)^2} \right\} \right] \tilde{\delta} \end{aligned} \quad (21)$$

Separating \tilde{v} , \tilde{i} terms and $\tilde{\delta}$ terms then

$$\begin{aligned} \dot{S} = & \frac{N\bar{\delta}}{2C} \tilde{i} - \frac{2}{R_0 C} \tilde{v} - k \frac{R}{L} \tilde{i} - k \frac{\bar{\delta}}{L} \tilde{v} + \\ & \left[k \frac{V_{in}}{L} \left\{ \frac{2R + NR_0(1-\delta)}{4R + NR_0(1-\delta)^2} \right\} - \frac{NV_{in}}{2C} \left\{ \frac{(2+2\delta)}{4R + NR_0(1-\delta)^2} \right\} \right] \tilde{\delta} \end{aligned} \quad (22)$$

Sliding mode will be there when $\dot{S} = 0$

The generalized control structure

$$u = -f(x) - k_1 \text{sign}(S) \quad (23)$$

From the above equation controlling signal $\tilde{\delta}$ is obtained

$$\tilde{\delta} = \frac{\left[-\frac{N\bar{\delta}}{2C} \tilde{i} + \frac{2}{R_0 C} \tilde{v} + k \frac{R}{L} \tilde{i} + k \frac{\bar{\delta}}{L} \tilde{v} \right] - k_1 \text{sign}(s)}{\left[k \frac{V_{in}}{L} \left\{ \frac{2R + NR_0(1-\delta)}{4R + NR_0(1-\delta)^2} \right\} - \frac{NV_{in}}{2C} \left\{ \frac{(2+2\delta)}{4R + NR_0(1-\delta)^2} \right\} \right]} \quad (24)$$

The control diagram of implemented controller is shown in fig 3. where, V_1 and V_2 are the module 1 and module 2 capacitor-voltages respectively. i_1, i_2, i_3, i_4, i_5 and i_6 are respective phase currents. V_1 is the DC link voltage input to the sliding mode controller for module-1 while V_2 is for the module-2. Similarly, i_1, i_2 and i_3 are the input to sliding mode controller of module-1 and i_4, i_5 and i_6 are the input to the module-2 sliding mode controller. Duty ratio is the output of the SMC and is used to generate PWM pulses to control the power switches.

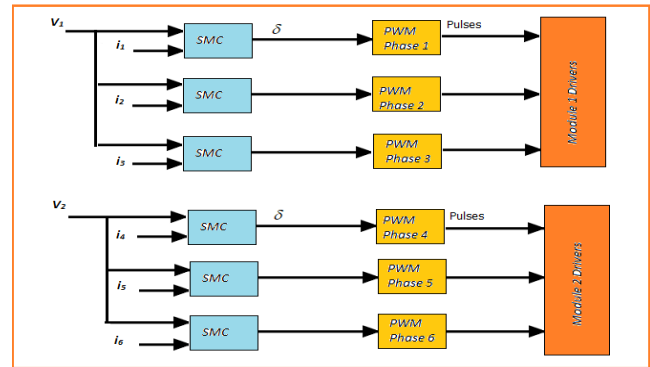


Fig. 5. Control Diagram of the implemented controllers

Parameter	Description	Value
R	Series Resistance	0.15Ω
L	Inductance	$535 \mu\text{H}$
C	Capacitance	$470 \mu\text{F}$
V_{in}	Input voltage	60 V
δ	Duty cycle	0.73
R_o	Load Resistance	59Ω
f_{sw}	Switching Frequency	10 kHz

V. SVPWM CONTROLLED VSI

Schematic diagram of a three-phase voltage source inverter is shown in Fig. 6. Space vector pulse width modulation technique is used to generate the pulses, which are used for the switches in the inverter.

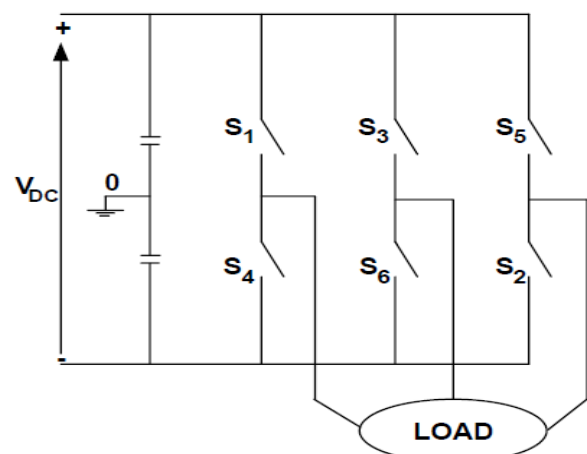


Fig. 6. Three-Phase VSI

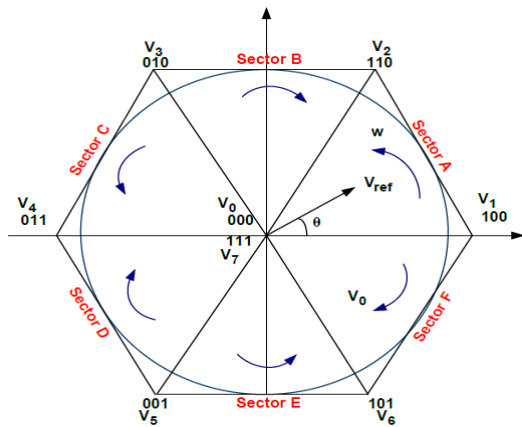


Fig. 7. Space vector diagram of the inverter

A hexagonal star diagram maps the eight base vectors are shown in Fig.7. Each vector constitutes a star spoken, with a phase difference of 60 degrees between adjacent vectors. The two vectors (V_0 and V_7) representing either all plus or all minus outputs are referred to as null vectors and are plotted in the star's center (origin).

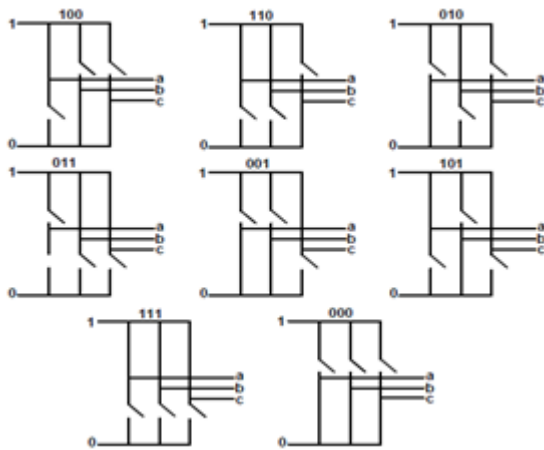


Fig 8. Three-Phase VSI Switching states

Each of the three binary digits corresponds to a bridge leg where the value 1 shows that the top transistor is ON while the value 0 shows that the bottom transistor is ON. All eight variations and the corresponding motor voltage and current direction are shown in Fig.8.

Inverter receives the gating pulses provided by SVPWM for ripple-free AC output voltage.

VI. PMSM DRIVE CONTROL STRATEGY

Permanent magnet synchronous motor (PMSM) systems have been used in many fields, because of the advantages of high speed, high precision, low maintenance and high reliability.

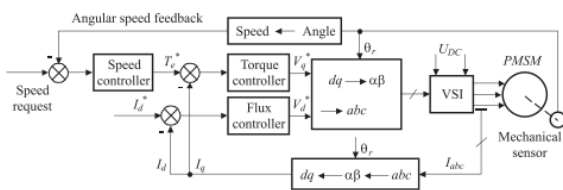


Fig. 9 PMSM Control

For a wide range of PMSM drives, the control systems have the same characteristics. The PMSM motion control system's

most popular control method is the cascaded one that uses traditional torque, speed, and position control techniques. By closing a feedback loop around the inner torque / current loop as shown in Figure. 9, The speed controller produces the torque request depending on the speed error. The stator current phasor is located only in the quadrature axis and the maximum driving torque is obtained by keeping the I_d current keeping at zero. This can be accomplished by setting to zero the necessary I_d^* current. By this method the pulses will be generated and given to inverter for getting required output.

VII. SIMULATION RESULTS

Fuel cell Driven PMSM Using IDDB Converter Based on Sliding Mode Control is modelled and its device output is tested on MATLAB / Simulink. The results of the parameters of the entire system are shown below. In this fuel cell, the results of simulation of IDDB converters with sliding mode controller, inverter and PMSM are explained under various load conditions.

The complete block diagram of Fuel cell Driven PMSM is shown in Fig 10. And the output voltage of fuel cell is shown in Fig.11 and its observed its value is nearly 60V.

In the IDDB the current flowing through the inductance are presented in fig12. From the above it is clearly observed the current in each inductance is varying from 10A to 20A respectively. Output current is shown fig13. In this it is observed the output current value is maintained constant.

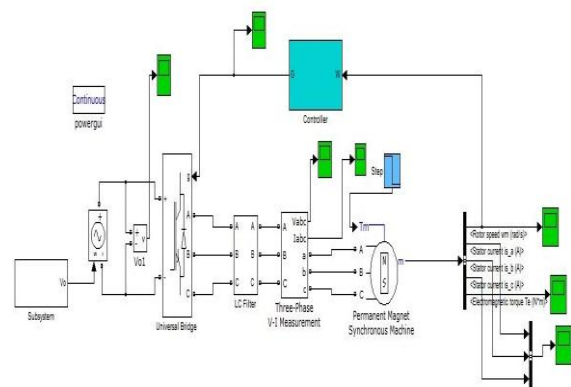


Fig.10. Simulink Model of Electric Vehicle

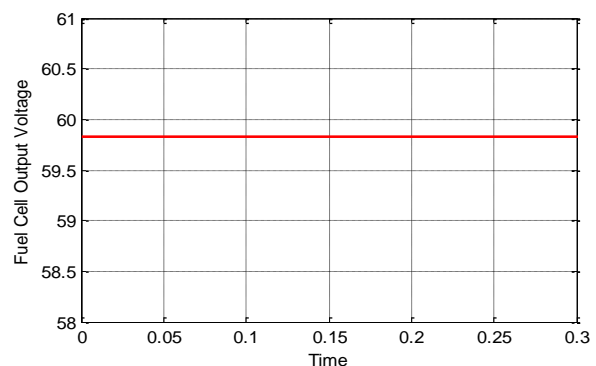


Fig.11 Output voltage of fuel cell

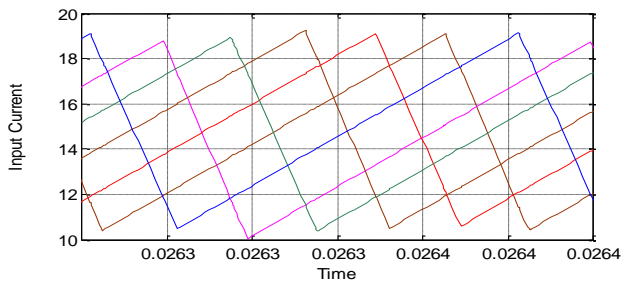


Fig.12 Input current of IDDB

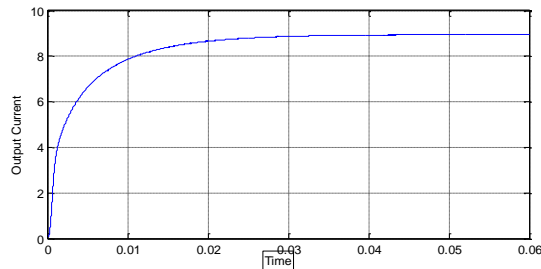


Fig.13 Output current of IDDB

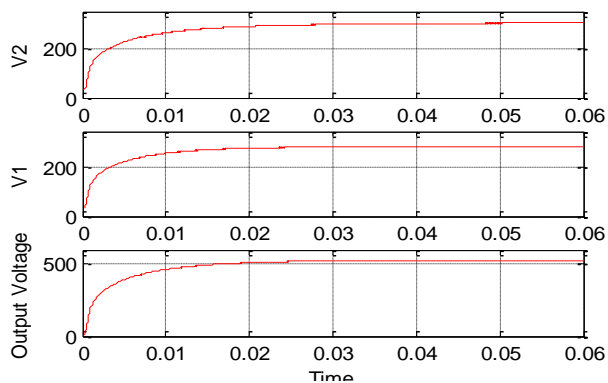


Fig.14. Output voltage of IDDB

The output voltages, voltage across the capacitors in both modules are shown in Fig 14. From the above the output voltage is regulated at the reference point and capacitor voltages are also constant from the given 60V input by using Sliding mode controller. It is clear from the above fig.8 that the fuel cell voltage, 60 V, is boosted to 500 V with the help of IDDB converter and maintaining constant 500 V at load side using sliding mode controller.

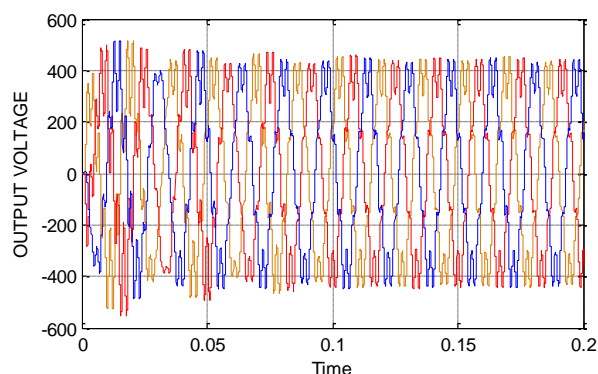


Fig. 15 output voltage of inverter

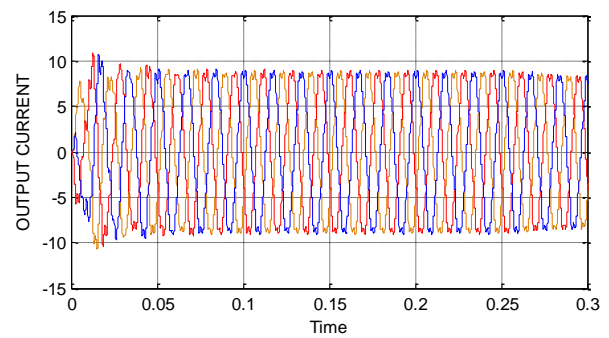


Fig. 16 output current of inverter

Inverter output voltage and current waveforms are shown in fig 15 and 16. From this the output voltage is nearly 450V whereas current is nearly 8A respectively, and this voltage is given to PMSM as an input voltage. Fig 17 to Fig 20 representing the speed and torque of PMSM under no load, step, repeated step and ramp load conditions. It is observed from the results, in all different load conditions the PMSM is operating in stable. In this paper, checked with until 5 N-m. Until 5 N-m in all different load conditions the controller is working more efficiently and motor also working Effectively.

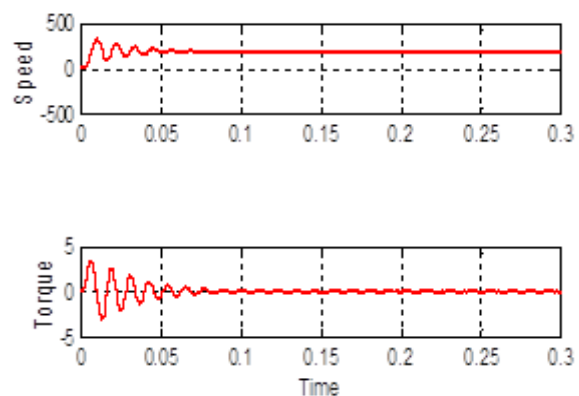


Fig.17 Torque and Speed of PMSM Under No Load

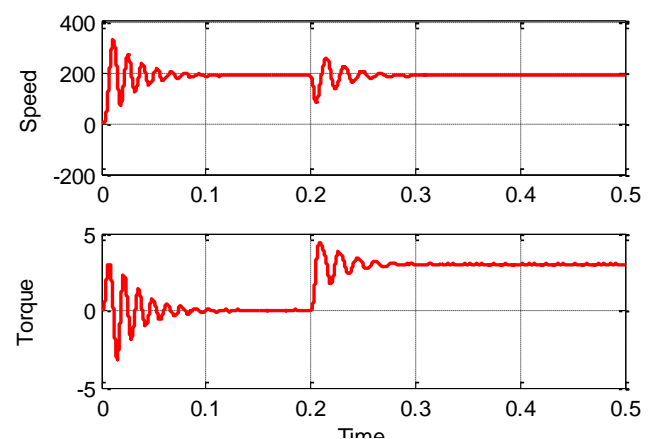


Fig.18 Torque and Speed of PMSM under Step Load

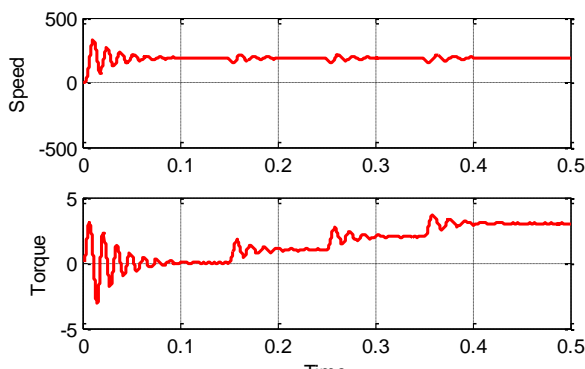


Fig.19 Torque and Speed of PMSM under repeated Step

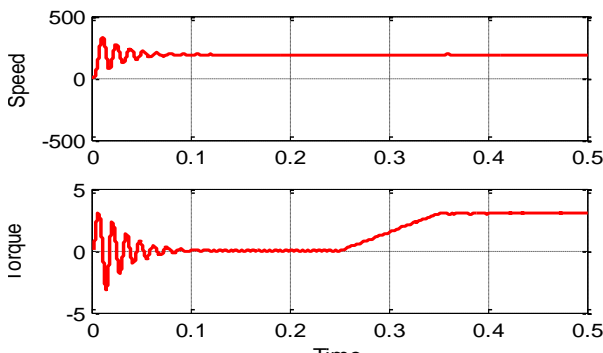


Fig.20 Torque and Speed of PMSM under ramp Load

VIII. CONCLUSION

The modeling and simulation of the Fuel Cell Driven PMSM Using Sliding Mode Control Based IDDB Converter is performed in this paper. The output voltage of the fuel cell stack is approximately 60 V. The power handling efficiency of IDDB increases with the number of phases is clearly observed, which means that the output voltage is greater for six IDDB phase compared to two IDDB phase. The inverter's output voltage is almost 400 V ripple-free using SVPWM and is supplied to PMSM. The motor performance is observed under various load conditions. It is clearly observed that under No load, step, repeated step and ramp load the PMSM is running stable. The theoretical research is accompanied by simulation performance.

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