# A Simple Method of Torque Ripple Minimization and Performance Characteristics Enhancement of Fuel Cell based PMSM Drives

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## ABSTRACT
Renewable energy sources are the promising alternatives for tackling the future energy crisis. Fuel cells are one of the upcoming non-conventional energy sources nowadays. Fuel cell based PMSM drives are finding positions in Hybrid Electric Vehicles, replacing the induction motor drives for they have many advantages such as high speed, high efficiency, high torque to inertia ratio, high power density etc., However the main problem in PMSM drives is the ripples produced in the torque. Also if these PMSM'S are used as such for HEV applications, then the performance of the HEV will not be satisfactory and the life span of the same will be lesser. Many methods have been proposed in literatures for the minimization of these ripples. In this paper a novel method of reduction of torque ripples and the enhancement of the other performance characteristics such sinusoidal input voltage and current, speed has been proposed. Further the main source of energy supply is the fuel cells. Hence this method is as a whole useful for PMSM drives which have fuel cells as their source of energy. The proposed method is validated by using MATLAB/SIMULINK. The conventional circuit and the proposed circuit are simulated and the simulated results are shown and compared. It has been observed that the proposed method gives rise to much minimized torque ripples and the enhancement of the above mentioned performance characteristics than when compared with the conventional circuit.

## Keywords
Non-Conventional Energy Sources, Fuel Cells, PMSM, Tri State CSI, Freewheeling state, Torque Minimization, Performance Characteristics.

## 1. INTRODUCTION
The tackling of energy crisis is one of the main areas of research. Other than conventional sources of electrical energy nonconventional energy sources such as wind turbine power systems, hydraulic turbine power system etc., are coming up nowadays. Fuel cells are one of the important sources of electrical energy. The first vehicle (EV) was built around 1834 and the EV concept has thus been around for almost 200 years. However, the EV had almost vanished from the market by 1930. This was mainly because of insufficient range, limited battery capacity, as compared to vehicles equipped with the Internal Combustion Engines (ICEs); a technology that was evolving rapidly at that time [1], [2]. A more mature generation of EVs was born in 1996 when General Motors Corporation leased their EV, named EV- 1, to customers in selected states of the USA. Unfortunately, once again, the attempt to introduce EVs to the customer market failed and, essentially, the worst deficiency of EVs is still their limited range [3].The drive train of a fuel cell vehicle (FCV) where the propulsion power is generated from a fuel cell is assisted by a super capacitor. For a current discussion on different types of EV and HEV drive trains [4], [5].PMSM drives are nowadays replacing the induction motor drives for they have many advantages such as high efficiency, high T/I ratio, higher speed, etc.,. Permanent magnet machines are, due to their high efficiency, power density, and torque to inertia ratio a common choice in EV and HEV concepts although other machine types, such as induction and switched reluctance machines, also have been adopted [4], [6]. Permanent magnet machines are, depending on the supply voltage waveform, divided into Brushless DC machines (BLDCs) which are fed with trapezoidal voltage waveforms and Permanent Magnet Synchronous Machines (PMSMs) which are fed with sinusoidal waveforms [7]. Both types are found in EVs and HEVs. However, in the present work the scope is limited and only PMSMs are considered. As pointed out before, adopting PMSM drives in EVs and HEVs can contribute significantly to improve the overall efficiency of the vehicle. Thereby, the operating range can be increased and for HEVs the fuel consumption is reduced. However the main problem in PMSM drives is the ripples produced in the output torque. A large number of techniques for torque ripple minimization has been proposed in literature [8]. Broadly speaking, these techniques fall into two major categories. The first class consists of techniques that concentrate on the motor design so that PMSM more closely approaches its ideal characteristics for achieving smooth torque production [9]–[11]. Although effective in ripple minimization, machine design techniques additionally complicate the production process and increase the final machine cost. The second class of algorithms, which is in our focus, consists of techniques for minimization of torque ripple using an additional control effort to correct for non ideal characteristics of the machine [12]–[19]. One popular approach is harmonic cancellation using the preprogrammed current waveforms [12], [13]. This method relies on knowledge of torque ripple characteristics of the specific motor, and uses the torque production model to calculate optimal currents that need to be injected to cancel the undesired torque components. Being based on off-line calculations, these techniques are sensitive to parameter variations and thus their performance degrades when the operating conditions change. To account for parameter variations during the motor operation, on-line estimation

techniques were proposed and reported in literature [14]–[19]. Estimation and control schemes are employed either in speed or current (torque) loops. Instantaneous torque controllers, for example, replace current loop with torque loop and use motor torque observers to obtain necessary feedback. Different methodologies have been proposed for torque observation (e.g., recursive least squares [16] and model reference adaptive system [17] techniques), and all of them extract information from the electrical subsystem (i.e., current measurements) to estimate the complete torque waveform. This waveform is then used as a feedback signal for the torque controller. Quality of current measurements enables accurate estimation, and control in the faster inner loop is effective in regulation of the output torque to the ripple free reference. On the other hand, this approach can be used only for those ripple components that are observable from currents—cogging torque and load oscillations can be minimized using this approach. The other possibility is to use mechanical variables (speed and position) in observation, and speed controller for ripple minimization [18], [19]. A simple method of torque ripple minimization was proposed by the author [21]. All possible sources of ripple are observable from mechanical states; hence this method has potential for complete ripple minimization. However, quality of speed feedback and slow dynamics of the outer loop limit the achievable performance of these algorithms. In this paper, a novel method of reduction of torque ripples of a fuel cell based PMSM drive has been proposed. The fuel cell feeds a tri-state current source inverter (which further feeds a PMSM) with only an additional semiconductor switch, which introduces unique freewheeling states apart from the traditional six active states and two null states. The appropriate insertion of freewheeling states into the inverter state sequence enhances the dynamic performance of the system and also reduces the ripples in the output torque. The inverter is controlled by the Space Vector Modulation technique.

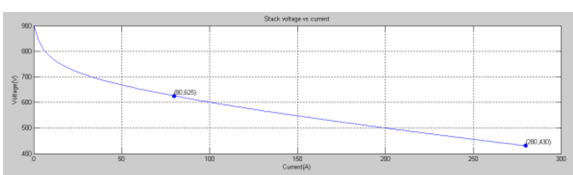

**Fig:1 Stack Voltage Vs Current Characteristics of Fuel Cell**

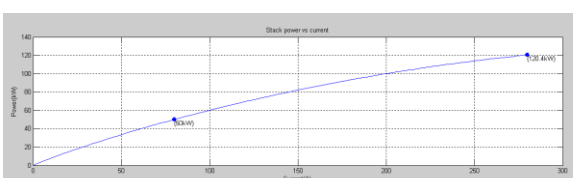

**Fig:2 Stack Power Vs Current Characteristics of Fuel Cell**

The performance characteristics of fuel cell viz., stack voltage Vs Current and Stack power Vs Current are shown in fig. 1 and fig.2

## 2. TRI-STATE CSI FED PMSM

The Tri-state current source inverter circuit feeding a three phase PMSM is shown in fig. 3 and is discussed in this section.

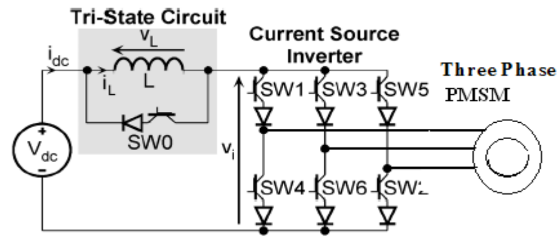


**Fig: 3 Tri-state CSI feeding a three phase PMSM**

The inverter has an additional unique freewheeling state is introduced by the connection of an extra semiconductor switch in series with a diode and by connecting this combination in parallel with the inductor as shown in fig 3. This inverter then feeds a three phase PMSM.

## 3.BLOCK DIAGRAMS

The block diagrams of a fuel cell based PMSM with conventional and the proposed method are shown and discussed in this section.

### 3.1 Fuel Cell based PMSM with the Conventional Approach

As seen in fig.4, the fuel cell generates a dc supply which is then fed to a boost converter. The purpose of using a boost converter in the circuit is to boost up the dc voltage to a level compatible for the inverter where the output of the inverter should again be compatible with that of the PMSM connected to it.

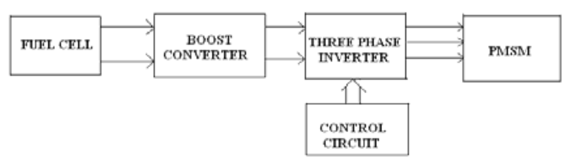


**Fig: 4 Block Diagram of a Fuel Cell based PMSM with Conventional approach**

The gating signals given to the inverter are in the conventional way. With this arrangement the PMSM starts rotating and its characteristic parameters are obtained.

### 3.2 Fuel Cell based PMSM with the proposed method

The block diagram of a fuel cell based PMSM with the proposed method is shown in fig.5.The control circuit includes the tri-state switching.

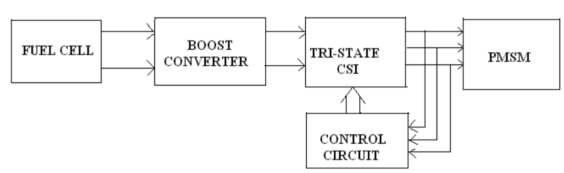


**Fig. 5 Block Diagram of a Fuel Cell based PMSM with the proposed method**

The block diagram of a Fuel Cell based PMSM with the proposed method is shown in fig. 5. The fuel cell generates a dc supply which is then fed to a boost converter. The purpose of using a boost converter in the circuit is again to boost up the dc voltage to a level compatible for the Tri-State inverter where the output of the inverter should again be compatible with that of the PMSM connected to it.

## 4. SIMULINK CIRCUITS

The simulink circuits of fuel cell based PMSM without and with the proposed method are shown and the circuit details are also presented.

### 4.1 Fuel Cell based PMSM with the Conventional Approach

The simulink circuit of a fuel cell based PMSM with the conventional approach is shown in fig.6

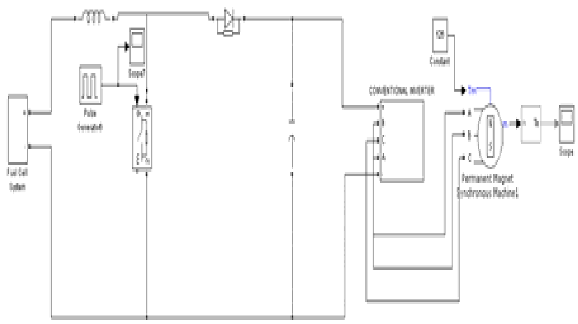

**Fig:6 Simulink Circuit of a fuel cell based PMSM with Conventional approach**

The first part of the circuit is fuel cell system in which the there are 65 fuel cells each connected in series so that the output voltage is 65, i.e., each fuel cell is capable of producing 1V. The operating temperature is $65^{o}$ and the nominal efficiency is 55%. A minimal cost can be achieved with respect to the fuel cells. The PMSM is rated at 560V. Therefore a boost converter is used in between the inverter and the fuel cell. This boost converter boosts the voltage up to 440 volts which should be the voltage input for the inverter to produce an output of 560V.The output of the inverter is then fed to a three phase PMSM and the output torque is observed using a scope.

### 4.2 Fuel Cell based PMSM with the proposed Method

The simulink circuit of a fuel cell based PMSM with the proposed approach is shown in fig.7.

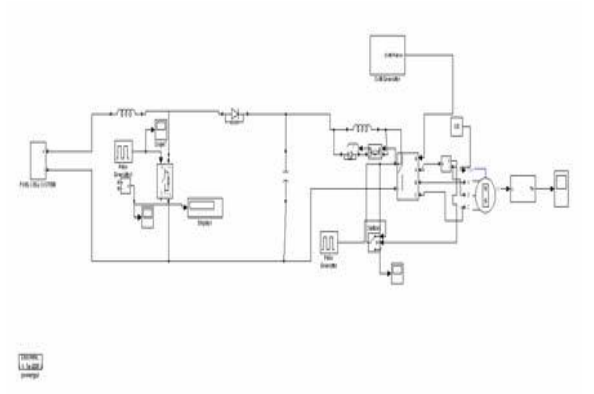

**Fig:7 Simulink circuit of a fuel cell based PMSM with the Proposed approach.**

The first part of the circuit is fuel cell system in which there are 65 fuel cells each connected in series so that the output voltage is 65, i.e., each fuel cell is capable of producing 1V. The operating temperature is 650 and the nominal efficiency is 55%. A minimal cost can be achieved with respect to the fuel cells. The PMSM is rated at 560V. Therefore a boost converter is used in between the inverter and the fuel cell. This boost converter boosts the voltage up to 440 volts which should be the voltage input for the tri-state current source inverter to produce an output of 560V.The output of the inverter is then fed to a three phase PMSM and the output torque is observed using a scope.

The switch SW0, is given with gating pulses, depending upon the state of the inverter, i.e., the gating pulses to the switch SW0 is given, when the inverter is at null state (i.e., 111 or 000 ). This makes the dc current to freewheel through the closed circuit formed with 'L', 'SW0" and the diode. At this stage, all the ripples in the supply side are filtered off. Also the output current of the inverter is sensed and given to a switch which consists of three input ports 1, 2 & 3. The output port of the selector switch is connected to the gate of the semiconductor switch SW0. The pulse generator is connected to port '1'.Thus whenever the output current of the inverter is zero, port 1 of the switch is selected so that SW0 is triggered ON and if the inverter current is not zero, input port 3 is selected, i.e., SW0 is left untriggered. Therefore, when input to u2 is zero, i.e., the output current of the inverter is zero, the input port '1'is selected and hence SW0 is turned ON and if u2 not equal to 0, input port '3' is selected and SW0 is turned OFF. This freewheeling also increase the energy stored in the inductor. And the moment the inverter regains the active states, the gating pulse to SW0 is withdrawn and the PMSM is supplied with a ripple free boosted energy (from the inductor).

## 5. WAVEFORMS AND OBSERVATIONS

This section discusses about the various waveforms obtained with the above discussed simulink circuits.

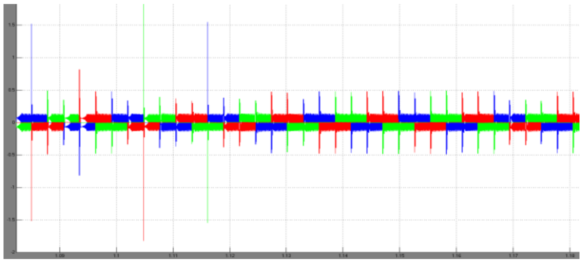

**Fig: 8 Stator Voltage(Volts) with the conventional approach**

The stator voltage of the PMSM i.e., the inverter output voltage with the conventional approach is shown in fig. 8. It can be observed that the waveform is full of ripples and the shape is also not sinusoidal even to an approximation.

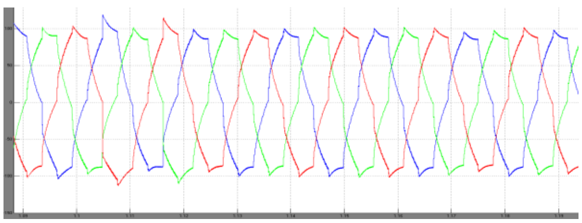

**Fig: 9 Stator Current(Amps) with conventional approach**

The stator current of the PMSM i.e., the inverter output current with the conventional approach is shown in fig. 9. It can be observed that the waveform is not purely sinusoidal.

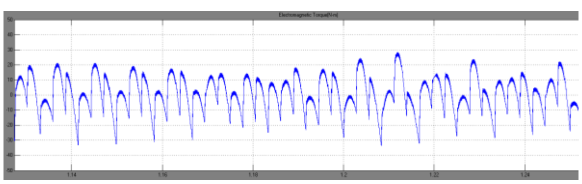

**Fig: 10 Torque(N-m) of the conventional approach**

The electromagnetic torque of the PMSM with the conventional approach is shown in fig. 10. It can be observed that the waveform is full of ripples, i.e., rich in ripples.If a HEV based PMSM has such a torque the performance of the same will be poor and so will be the life of HEV.

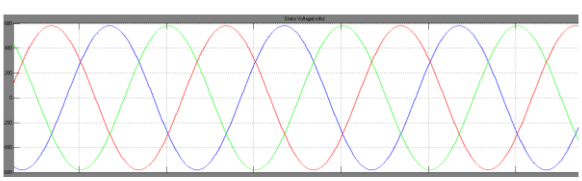

**Fig: 11 Stator Voltage(Volts) with the proposed approach**

In fig. 11 is shown the inverter output voltages for all the three phases of the proposed circuit.It is seen that these are purely sinusoidal and are displaced from each other at proper angles.

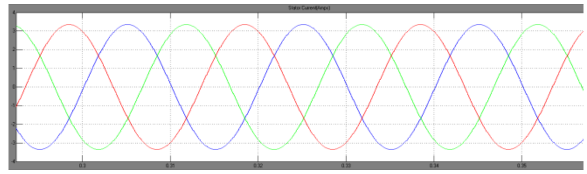

**Fig: 12 Stator Current(Amps) with the proposed approach**

Fig 12 shows the stator current of the PMSM, i.e., the inverter output current for all the three phases with the proposed circuit.The currents are purely sinusoidal with no ripples.If such currents are fed as input to the PMSM then the motor will give good performance with no over heating of the windings(produced due to the harmonics/ripples).

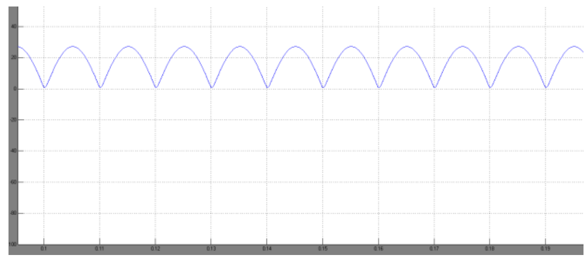

**Fig: 13 Electromagnetic Torque (N-m) with the proposed approach**

The electromagnetic torque(N-m) of the PMSM with the proposed method is shown in fig. 13.The waveform reveals that the ripples are reduced drastically than when compared with that produced by the conventional approach. With such a torque the performance of the HEV will be good and hence the life span of it will be increased.

## 6. CONCLUSION

Renewable energy sources are the promising alternatives for meeting the future energy crisis. Fuel cells are the upcoming non-conventional energy sources nowadays. Fuel cell based PMSM drives are used as Hybrid Electric Vehicles. However the main problem in PMSM drives is the ripples produced in the torque. Also if these PMSM are used as such for HEV applications, then the performance of the HEV will not be satisfactory and the life span of the same will be short. Many methods have been proposed in literatures for the minimization of these ripples. A novel method of reduction of torque ripples has been proposed in this paper. The main source of energy supply is the fuel cells. Hence this method is as a whole useful for PMSM drives which have their source of energy as fuel cells. The proposed method is validated by using MATLAB/SIMULINK. The proposed circuit and a conventional circuit are simulated and the simulated results are shown and compared. It has been observed that the proposed method, which has a fuel cell feeding a boost converter which further feeds a three phase tri-state CSI gives rise to minimized torque ripples and improved performance characteristics than when compared with the conventional circuit. This means that a HEV based on the proposed circuit improves the performance of the entire system and so the life span of the HEV is also increased.

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