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Speed Control of EF_2 Resonant Converter Fed PMSM Drive for Fuel Cell Vehicles

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Abstract: Fuel Cell Vehicles (FCV's) are gaining more attention in the present scenario as it overcomes the disadvantages of internal combustion engine vehicles and electric vehicles. FC technology for automotive applications is an attractive prospect for automotive manufacturers and consumers. But one of the main barriers for the adoption of FCV's is the increased cost of fuel cell stack. Also the FC stack voltage reduction while accelerating is another problem as power reduces at high speeds with increase in current. This paper presents a 10 hp PMSM drive with reduced size and cost with 8 KW fuel cell stack for FCV applications fed from EF_2 resonant converter which improves the dynamic performance and system reliability. The simulation result which validates the enhanced performance is also produced.

Keywords: fuel cells (FC's), fuel cell stack, dynamic response, reliability.

I. INTRODUCTION

Fuel cell vehicles powered by pure Hydrogen (H_2) emit no tailpipe greenhouse gases, only heat and water. Researches indicate that the total CO_2 emissions for a FCV can be 75% less than the equivalent diesel vehicle [1]. Secondly FCVs could reduce our dependence on foreign oil since H_2 can be derived from domestic sources. FCVs are superior to battery vehicles as they have more range, less weight and lesser refueling time.

The output voltage of a single fuel cell is about 0.6 to 0.8V which is very low for practical applications [2]. Hence a number of cells are connected in series to form a fuel cell stack along with a power electronic converter to boost the stack voltage to the required value. But the fuel cell stack voltage reduces with the increase in current and is a major disadvantage in these types of vehicle. The FC voltage drops to about 10% in the normal load region and about 30% in the high load region due to activation loss, ohmic loss and concentration loss. When fuel cell vehicle accelerates specially to high speeds, the current flow from the fuel cell increases and the ohmic resistance of the membrane makes the voltage to drop. As a result the power decreases at high speeds, which is not at all desirable [3].

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The operation of FCV's is explained through the block diagram in Fig 1. The FC stack voltage is increased to the required level by means of a suitable boost converter. During transient conditions and high load period FC itself cannot provide the required power to the electric motor [4]. Hence an auxiliary power source such as battery or super capacitor must be incorporated in order to provide additional voltage as and when required and is shown as battery pack [5]. The boosted output voltage is supplied to the motor from where the power is transferred to the wheels, through clutch and gear box mechanism.

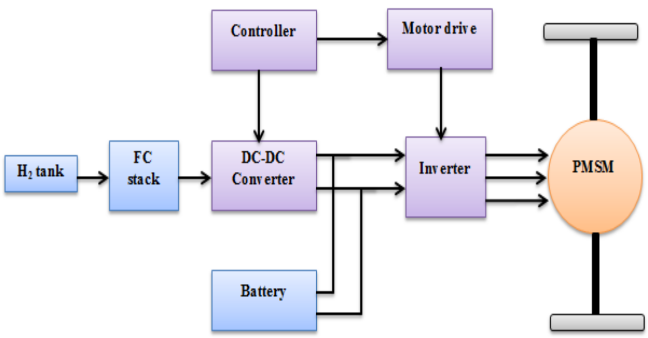

Fig1. Fuel Cell vehicle block diagram

The power electronic converter plays an important role in FCV's. Different types of DC-DC converters were used to boost the fuel cell stack voltage [6,7]. Non isolated converters such as interleaved boost and Single ended primary inductor converter (SEPIC) have pulsating input current, high voltage stress and increased output current ripple [8]. The power electronic converters are preferred to be isolated to provide safety for the loading devices. But the leakage inductance of the transformer leads to high voltage stresses across the converter switches. Isolated converters also suffer from poor transient response, high conduction loss, low efficiency and lower power handling capability. Multilevel inverters are also used which reduces the harmonics in the output voltage which in turn improves the efficiency of the motor. But the control is more complex due to the increased number of switches.

The main problems of the existing DC-DC converter topologies in FCV's are the limitation in switching frequency and duty ratio. The maximum boosted voltage that can be obtained is limited due to the limitation in duty ratio. Hence the input voltage from the fuel cell stack has to be increased to obtain the required boosted voltage. This increases the cost of fuel cell stack as more number of fuel cells has to be connected in the stack.

Power density and efficiency of energy conversion are the other concerns of power converters used in FCVs. To increase the power density, size of passive components must be reduced and can be achieved by operating at higher frequencies. Also at higher switching frequency, smaller time constants are achieved which provide the converter faster dynamic response and is very important in vehicular applications.

Resonant converter is the best solution for the above problems [9]. The essential advantage of the resonant converter is the soft switching which reduces the switching losses during high frequency operation. Resonant converters are capable of operation at higher switching frequency in MHz range which reduces the size of passive components with increased boosting operation Class D resonant converter has simple principle of operation but they are less efficient for higher switching frequency[10]. Recently class E resonant DC-DC converters were used to boost the fuel cell voltage. But the main disadvantage of class E resonant inverter is its high peak voltage across the switch reaching upto 3.5 times the DC voltage at a duty cycle of 0.5.[11]. Class F resonant converter shapes the voltage and current waveforms by eliminating the harmonics present. But the tuning is complex and control is difficult.

Brushless DC motor, Switched Reluctance Motor (SRM) and Permanent Magnet Synchronous Motor (PMSM) are mainly used in FCVs [12, 13]. Pulsating torque and motor overheating are the main disadvantages associated with Brushless DC (BLDC) motor drives. SRM drive has rugged construction and is capable of high speed operation. But the control is complex because it is difficult to sense the minimum reluctance position. Giving more emphasis to reliability, PMSM is the best choice because it has higher efficiency, torque and power density compared to other motors [14, 15].

In this paper, EF$_2$ resonant converter is proposed to boost the fuel cell stack voltage instead of DC-DC converters. The output voltage can be boosted to the required value from a very low input voltage (12V-120V) without compromising the output current and duty cycle compared to the existing topology. The main advantages of this topology include reduced current stress, enhanced power output capability and low Total Harmonic Distortion.

Section II deals with the working and design of EF2 resonant converter. Section III and IV deals with the modeling of Polymer Electrolyte Membrane FC (PEMFC) stack and PMSM drive. Section V deals with the simulation results.

II. CLASS EF$_2$ RESONANT CONVERTER

EF2 Resonant converter consists of an inverter and rectifier section coupled with a transformer.

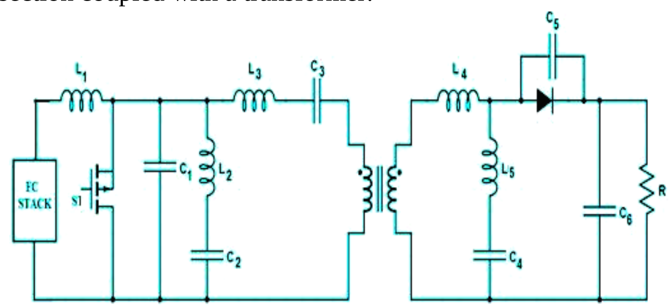

Fig2. Class EF2 Resonant Converter

The converter has 2 modes of operation. When the switch is OFF , the input current flows through the resonant circuits and energy is transferred to the secondary of the transformer which is then rectified [16]. When the switch is ON, the inductor L1 charges. Energy transfer takes place between the resonant circuits and is transferred to the secondary of the transformer which is then rectified. Hence it acts as a DC-DC converter.

The converter is designed for 12V input and 120V output for an output power of 8KW and switching frequency 1MHz.The input voltage is boosted to 4 times at the primary of the coupling transformer by adjusting the quality factor of resonant circuit. Further boosting is done by adjusting the turns ratio of the transformer. The main design equations are:

Inverter Section:

$$L_1 = \frac{2\pi D\, V_{in}}{\omega_s \Delta i_{Lmax}} = 67.4\ nH \qquad (1)$$

$$c_1 = \frac{I_{in} * 5.324}{2\pi\omega_s \times V_{in}} = 7.49\ \mu F \qquad (2)$$

For maximum power transfer $= \frac{c_1}{c_2} = 0.867$, $c_2 = 8.63\ \mu F$

Resonant frequency = $2f_s$

$$L_2 = \frac{1}{\omega_0^2 c_2} = 0.73\ nH \qquad (3)$$

$$\frac{1}{\omega_s R_L c_3} = \theta_L - \frac{\omega_s L_3}{R_L} \qquad (4)$$

$L_3 = 0.9\ nH$ $\quad C_3 = 1.49\ \mu F$

Rectifier Section:

$$L_1 = \frac{2\pi D\, V_{in}}{\omega_s \Delta i_{Lmax}} = 13.56\ \mu H \qquad (5)$$

$$c_1 = \frac{1}{1.813\ \omega_s R_L} = 91.5\ pF \qquad (6)$$

$$c_2 = 105.5\ pF,\ L_2 = \frac{1}{\omega_0^2 c_2} = 60\ mH \qquad (7)$$

III. MODELING OF PEMFC STACK

In FCV's instead of a single fuel cell stack, several stacks are connected in parallel to increase the power rating. A 1KW 12V stack is modeled and 8 such stacks are connected in parallel at the input. The main equations are:

Let T = $25^o C$, i = 0.8 A/cm^2, $i_1 = 1.4\ A/cm^2$

Area of a cell = 104 cm^2, Pressure of air and $H_2 = 3\ atm$

$$PP_{H_2} = \frac{0.5 * P_{H_2} * T^{1.334}}{e^{1.653i}} - P_{H_2O} \qquad (8)$$

$$PP_{O_2} = \frac{P_{air} * T^{1.334}}{e^{4.192i}} - P_{H_2O} \qquad (9)$$

$$E_{nernst} = -\frac{G}{2F} - \frac{1}{2F}\left\{R * T\ log\left[\frac{P_{H_2O}}{PP_{H_2} * \ PP_{O_2}^{\ 0.5}}\right]\right\} \qquad (10)$$

$$V_{act} = \frac{R*T}{2\alpha F} log\frac{i}{i_o} \qquad V_{ohmic} = i * r \qquad (11)$$

$$V_{con} = \alpha * i^k * \log(1 - \frac{i}{i_1}) \qquad (12)$$

$$V_{FC} = E_{nernst} - V_{act} - V_{con} - V_{ohmic} \qquad (13)$$

$$V_{stack} = V_{FC} * Ncells \qquad (14)$$

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The Simulink model of PEMFC stack is shown in Fig 3. The first block represents the calculation of partial pressure and the second one the calculation of losses in fuel cell. The simulation results and the V-I characteristics of the model is shown in Fig 4 and 5.

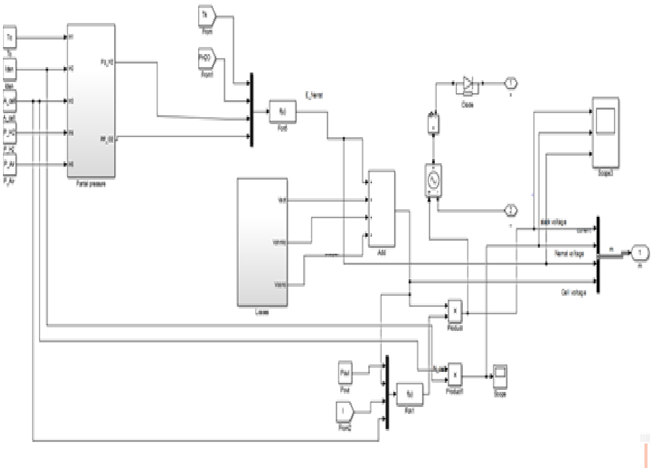

Fig3. Simulink Model of PEMFC stack

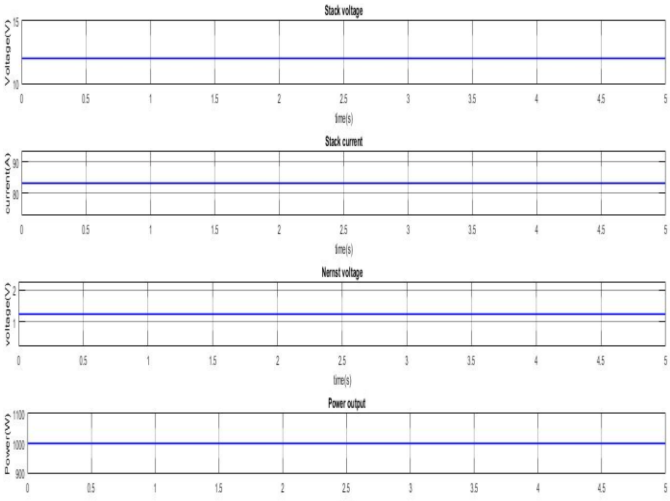

Fig4. PEMFC stack voltage and current

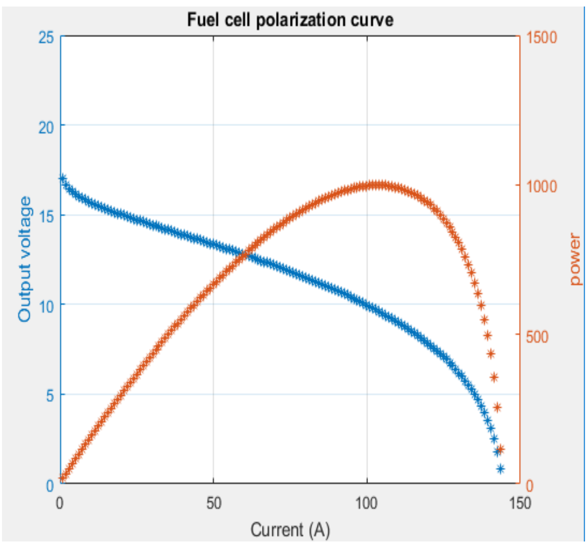

Fig5. Polarization curve of PEMFC stack

In the PEMFC stack modeled, the individual cell voltage is 0.6 V. Hence 19 cells are connected together in a single stack to provide 12 V. 8 such stacks are connected in parallel and is connected to the EF_2 resonant converter. The simulation diagram is shown in Fig 6.

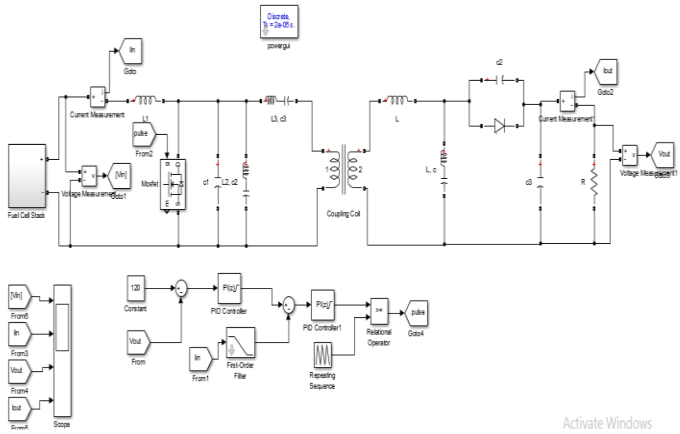

Fig. 6 Closed loop simulation of PEMFC stack with converter.

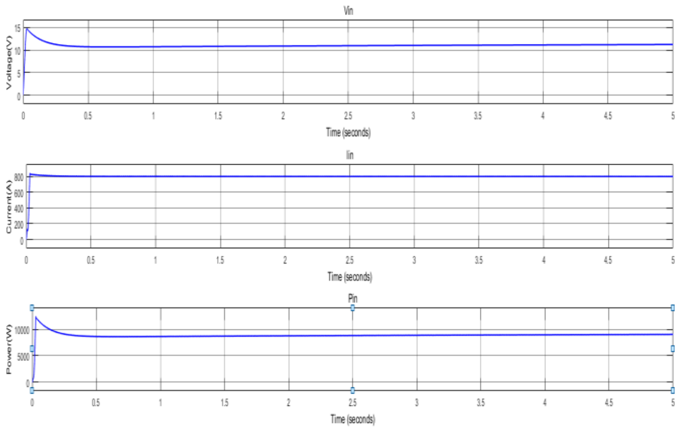

Fig7. Input voltage, current and power of EF_2 converter

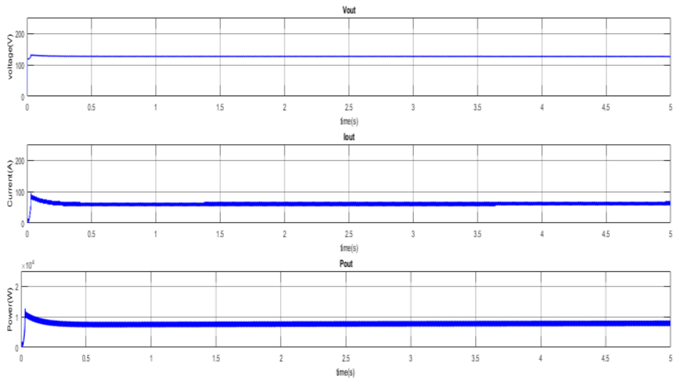

Fig8. Output voltage, current and power

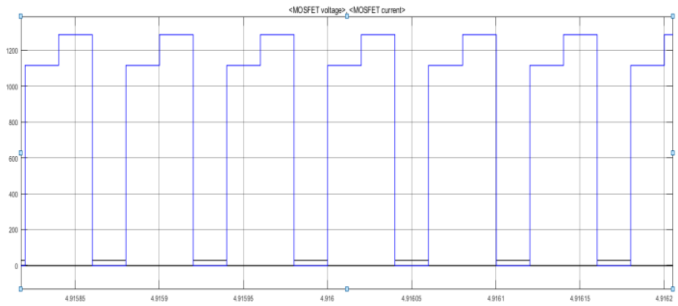

Fig9. Soft switching waveforms

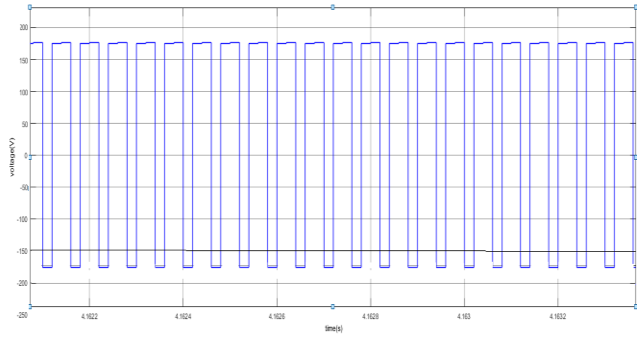

Fig10. Transformer secondary voltage

From the simulation results we can see that input and output power is about 9000W. Also the switch is undergoing zero voltage turn ON and zero current turn OFF inorder to minimize the losses. Transformer secondary voltage is about 170V which is rectified and we are getting 120V at the output of the converter to drive the PMSM.

Hence we can see that from a very low voltage of 12V, we are obtaining an output of 120V. So the number of cells in the stack can be reduced compared to the conventional topologies and the size and cost of the FC stack can be reduced which is very much beneficial for FCV's.

IV. MODELING OF PMSM DRIVE

A 10 hp, 3500 rpm PMSM is modeled and the main design equations are:

For 10 hp -3500 rpm , 120 V motor Tmax = 30 Nm

f=50 Hz , pf=0.8

$$V_d = R_s i_d + L_d \frac{di_d}{dt} + \frac{d\lambda_f}{dt} - \omega_r L_q i_q \qquad (15)$$

$$i_d = \int \left(\frac{V_d}{L_d} - \frac{R_s}{L_d} i_d + \frac{\omega_r L_q i_q}{L_d}\right) dt \qquad (16)$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r \lambda_f + \omega_r L_d i_d \qquad (17)$$

$$i_q = \int \left(\frac{V_q}{L_q} - \frac{R_s}{L_q} i_q - \frac{\omega_r L_d i_d}{L_q} - \frac{\omega_r \lambda_f}{L_q}\right) dt \qquad (18)$$

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_f i_q - i_d i_q (L_d - L_q)\right] \qquad (19)$$

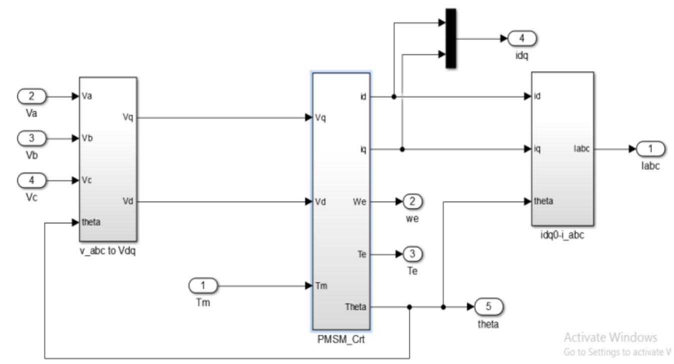

Fig 11.Simulink model of PMSM drive

Inorder to model the PMSM drive, the 3 phase voltage equations are converted to d-q reference frame by Park's transformation. From the torque and d-q voltages, the d-q currents are obtained and then transferred to 3 phase variables by inverse Park's transformation.

V. SIMULATION RESULTS

Table I. Specifications used

Component	Specifications
PEMFC stack	12V, 1KW stacks in parallel (8 nos)
EF_2 Resonant Converter	V_{in} = 12V V_{out} =120V f_s =1MHz P_{out} =8 KW
PMSM drive	10hp, 120V, 3500 rpm, T_{max} = 30 Nm

To validate the enhanced performance of a FC motor cycle with 10hp PMSM drive, the EF_2 resonant converter with PEMFC stack is connected to the modeled PMSM drive and is simulated using MATLAB. The overall specifications of the vehicle used and speed torque requirements of the vehicle is shown in Table I and II.

Table II. Speed Torque Requirements of vehicle

Condition	Torque (Nm)	Speed (rpm)
Starting	30	1000
Climbing	24	1800
Smooth Road	15	3500
Braking	0	0

The complete closed loop simulation diagram is shown in Fig 12. Maximum torque is required at starting condition and then the torque decreases and speed increases. The converter output voltage is regulated at 120 V and the current is adjusted to obtain the required power for different operating conditions. The output of the converter is fed to the inverter to drive the PMSM.

To control the motor torque, the actual speed of the motor is sensed and is compared with the reference speed. The error signal obtained is fed to the PI controller to control the q axis reference current. In torque control, the flux is kept constant and hence d axis current is set to 0. The switching pulses for the inverter is generated by sinusoidal pulse width modulation scheme.

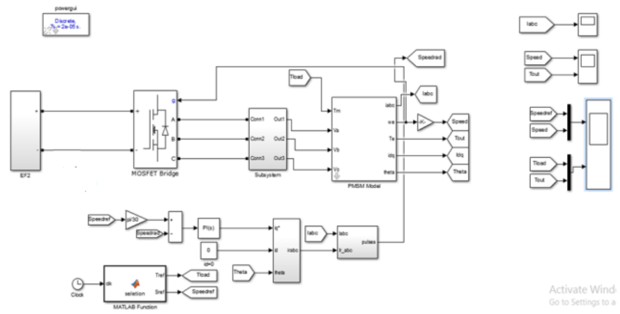

Fig 12. Complete Simulation diagram

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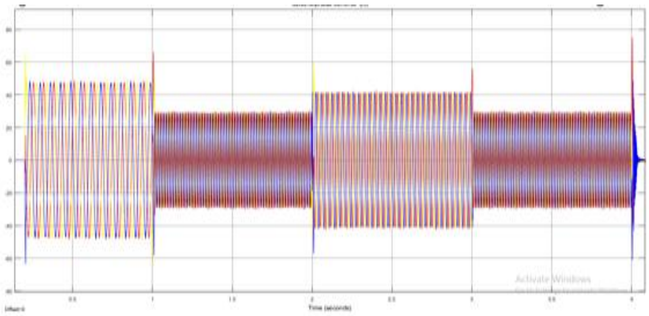

Fig13. Motor 3 phase currents

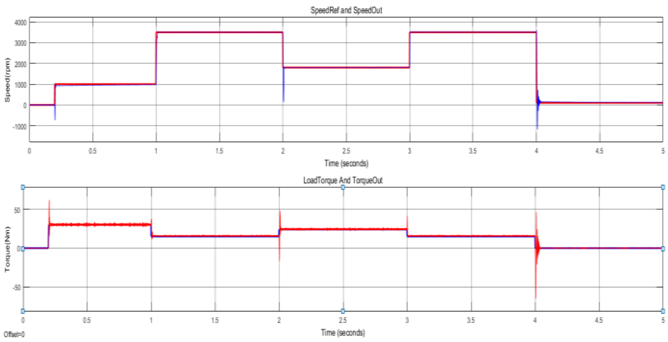

Fig14. Reference and actual speed and torque

The simulation results are shown in Fig 13 and 14. The starting condition is shown from 0.25 to 1s. From1 to 2s, the smooth road condition, climbing condition from 2 to 3 s, again smooth road condition from 3 to 4 s and finally braking at 4s is shown. Maximum torque is required at the starting condition. At smooth road, lesser torque is required and speed has to be increased. During climbing, again torque has to be increased and speed decreases.

Whenever the motor requires more torque, the 3 phase currents of the PMSM is increased and the required power is obtained so as to increase the torque with decrease in speed and vice versa. Also we can see that the actual speed and torque tracks the reference value effectively by closed loop control. The rise time and settling time for speed and torque waveforms for each condition is shown in Table III. The torque ripples can be minimized by other advanced control methods.

Table III. Speed and torque waveform analysis

Condition	Rise time (ms)	Settling time(ms)
Starting	1.2	9.7
Smooth road to climbing	0.98	3.8

VI. CONCLUSION

The main obstacles for the adoption of FCV's are increased cost of fuel cell stack, limited voltage boosting capability of the converter and limitation in switching frequency of the converter. Using EF_2 resonant converter for voltage boosting, will solve all the above disadvantages. The number of cells in the fuel cell stack can be decreased because of the high voltage boosting capability of the converter with increased switching frequency which will reduce the cost of fuel cell stack thus enhancing the reliability of FCV's. The simulation results which validate the enhanced performance were also presented.

REFERENCES

1. T. J. Kirkland , R. Jasinski," Fuel Cells - State of the Art", *IEEE Transactions on Industrial Electronics* [May 1963] Year: 1963 , Volume: IE-10 , Issue: 1, Page s: 112 - 124.
2. A. Emadi; S. S. Williamson," Fuel cell vehicles: opportunities and challenges" *IEEE Power Engineering Society General Meeting.*Year: 2004, Vol.2, Pages: 1640 -1645.
3. T. Gilchrist, "Fuel cells to the fore [electric vehicles]", *IEEE Spectrum* Year: 1998, Volume: 35, Issue: 11, Pages: 35 – 40.
4. C C Chan, "The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles", *Proceedings of the IEEE* Vol. 95, No. 4, April 2007.
5. Shirin Espiari," Transient Response of PEM Fuel Cells During Sudden Load Change", *2010 IEEE International Energy Conference.*
6. Huang-Jen Chiu, "A Bidirectional DC–DC Converter for Fuel Cell Electric Vehicle Driving System", IEEE Transactions on Power Electronics, Year: 2006, Volume:21, Issue:4, Pages: 950-958
7. Yun Zhang," A Wide Input-Voltage Range Quasi-Z-Source Boost DC–DC Converter With High- voltage Gain for Fuel Cell vehicles" , *IEEE transactions on industrial electronics*, vol. 65, no. 6, june 2018.
8. Chih-Lung Shen ; Po-Chieh Chiu," Buck-boost-flyback integrated converter with single switch to achieve high voltage gain for PV or fuel-cell applications**",** *IET Power Electronics,* Year:2016, Volume: Issue: 6 Pages: 1228 – 1237.
9. Marian k. Kazimierczuk," Resonant dc/dc Converter with Class-E Inverter and Class-E Rectifier", *IEEE transactions on industrlal electronics*, vol. 36, no. 4, november 1989
10. Juan A. Santiago-Gonz´alez," Design of Class E Resonant Rectifiers and Diode Evaluation for VHF Power Conversion", *IEEE transactions on power electronics*, vol. 30, no. 9, september 2015
11. D. C. Hamill, "Class *DE* inverters and rectifiers for DC-DC conversion", *IEEE Power Eletronics Specialists Conference*, vol. 1, pp. 854-860, 23- 27 Jun 1996.
12. By Z. Q. Zhu," Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles", *Proceedings of the IEEE* Vol. 95,No. 4, April 2007.
13. C. Bader ; W. Stephan" Comparison of electrical drives for road vehicles**",** *IEEE Transactions on Vehicular Technology* Year: 1977 , Volume: 26 , Issue: 2 ,Page s: 123 – 128.
14. J. Fang, C. Heising, V. Staudt na dA. Steimel, "Permanent-magnet synchronous machine model for urban transport applications," *12th Int. Conf. on Optimization of Electrial and Electronics Equipment, OPTIM.* 2010.
15. I C.Chakraborty and Y.Hori, "Fast Efficiency Optimized Technique for the Indirect Vector Controlled Induction Motor Drives," *IEEE Trans. Ind. Appl.*,Vol.39, 2003,pp.1070-1076.
16. Samer Aldhaher, David C. Yates, "Modelling and Analysis of Class EF and Class E/F Inverters with series-tuned resonant networks", *IEEE Transactions on Power Electronics*, Year: 2016, Volume: 31, Issue: 5, Pages: 3415-3430.

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