MPC based Hybrid Battery and Fuel cell powered PMSM drive for Electric Vehicle Applications

Ramesh G.P [1], R. Pandiaraj [2]

[1]Professor of Electronics and Communication Engineering, St.Peter's University, Avadi, Chennai, Tamilnadu, India.

[2] PG Student, Power Electronics and Drives, Department of Electrical and Electronics Engineering, St.Peter's University, Avadi, Chennai, Tamilnadu, India.

[1] rameshgp@yahoo.com,[2] pandiaraj.r@gmail.com

Abstract

Permanent magnet synchronous motor is a robust machine for electrical vehicle application which can provide maximum torque at starting with low power and control of such machine is complex. This paper presents a model based predictive methodology for current control for PMSM drive powered through hybrid battery and fuel cell sourced electrical vehicle. Advantage of a MPC controller is it can predict the future changes in the system based on past and present inputs and enhances the dynamic performance of the PMSM control system. MPC controller increases the efficiency of the proposed system by ensuring precise control over output current from the drive. A buck-boost converter is employed to provide optimum dc link performance required for the voltage source inverter fed PMSM motor. The main objective of the buck boost converter is to boost the voltage available from battery and fuel cell even during low state of charge regions for stable operation of the drive. A suitable electrical vehicle model was developed in MATLAB/Simulink environment to validate the advantages of proposed conversion and control system for PMSM drive.

Keywords: *Permanent Magnet Synchronous Motor (PMSM), Electrical Vehicle, Fuel Cell, Model Predictive Controller (MPC), Buck-Boost Converter*

1. INTRODUCTION

In recent years the conventional IC engine powered vehicles are replaced with electric/hybrid electric vehicles to minimize the utilization of conventional fuels and to provide green environment with less pollution. The general structure of an EV or HEV consists of an energy storage system, power electronic conversion system, electrical machine or motor and an energy management based control unit. For electrical vehicle applications PMSM motor is preferred over other electrical motors due to its advantages. It shows better performance such as improved starting torque at even full load, high efficiency and low losses. The only disadvantage of PMSM

Issn No:0975-0932

motor is ripples in developed torque due to poor control methodology and design. The main advantage of this type of machine is its characteristics shown during regenerative braking which is utilized to save energy during braking condition. However to regenerate power during braking motor should be running at a stable speed, it is not possible at low speeds.

A performance comparison is made for the use of Induction motor and PMSM motor for the use of electric vehicle [1]. Battery powered electric vehicles based on PMSM motor is preferred due to its robustness [2]. However PMSM motors require high performance controllers [3-5] to deliver high power even at starting. Flux weakening controllers are helpful to run the motor at a speed above its base speed and to minimize torque pulsations developed during PMSM motor operation precise current controllers are required. Fuel cell [6] is proposed as a source for electrical vehicles based on PMSM motors and a comparison is made between the electric vehicles which uses battery and fuel cell as their sources [7]. Use of such hybrid sources [8] for electrical vehicles is appreciated which reduces the overall operating cost of the vehicle. MPC is a modern controller applicable to various process control systems, use of such a controller for PMSM motor control is proposed in [9]. For minimizing the ripples occurring in torque MPC is used as a predictive torque and flux controller [10] for PMSM motor control. Indirect torque control is achieved by means of predictive current control [11-12] provides highly regulated stator current with less ripples in torque. This paper proposed a hybrid source battery and fuel cell for electrical vehicle comprises of VSI driven PMSM motor whose control is governed by predictive current control methodology. Further a buck boost converter is introduced to allow bidirectional power flow from source to machine and machine to hybrid source. Overall configuration of the proposed electrical vehicle system is given in next section.

2. Overall Configuration of Proposed System

Functional Diagram of the proposed electrical vehicle system is shown in the fig 1. It consists of two sources a battery and a fuel cell both the sources have the capability energy discharging and charging. Detailed modeling of fuel cell with equivalent circuit and characteristic equations are presented in section III. The proposed system involves two power electronic conversion systems one acts as a bidirectional buck-boost dc-dc converter and other converter acts as a voltage source inverter which drives the PMSM motor. Mathematical model of PMSM motor is given in section IV. A model predictive current controller is preferred for PMSM motor control which provides stable operation with uncertainties and non linear design. The advantage of this type of controller is it predicts future PWM cycle for inverter depends on past and present current values. This controller provides a high accuracy over current control which in turn used to provide smooth output torque from motor even during sudden load varying conditions.

Issn No:0975-0932

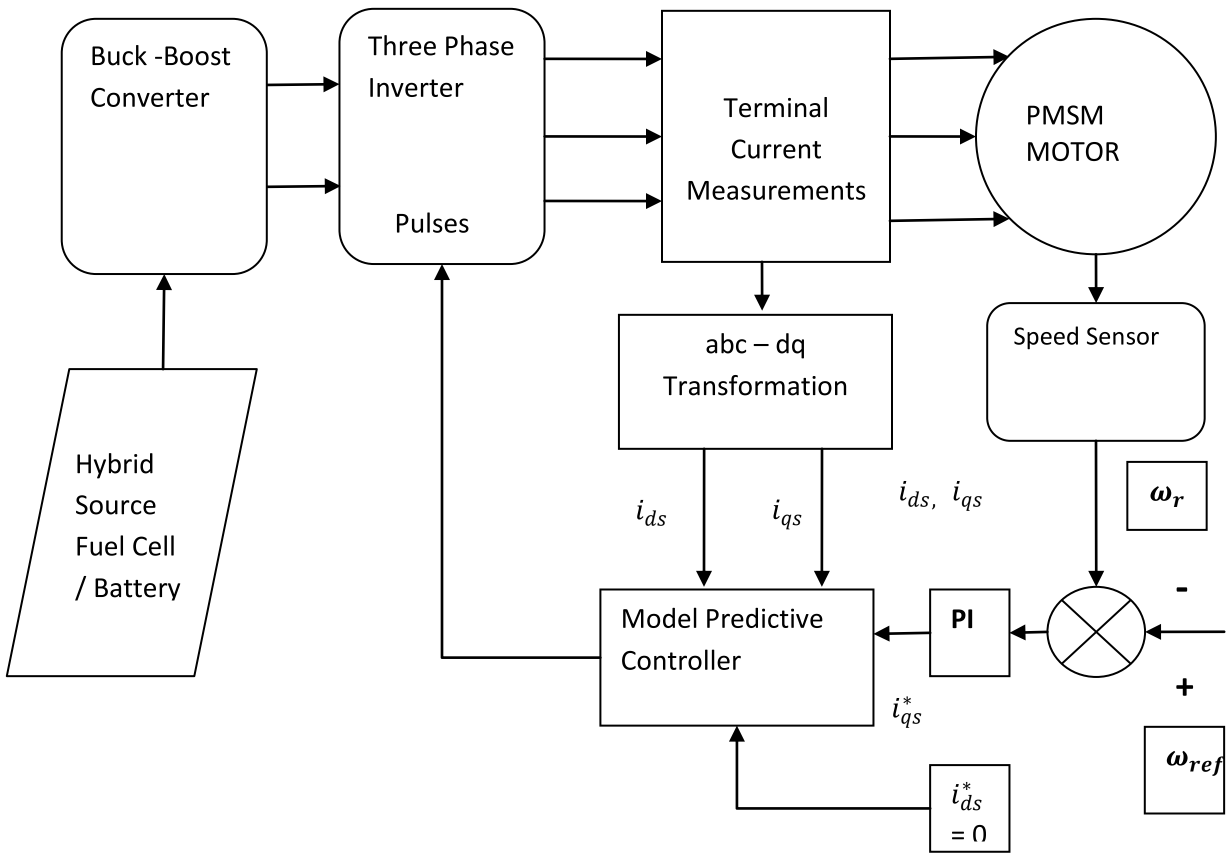
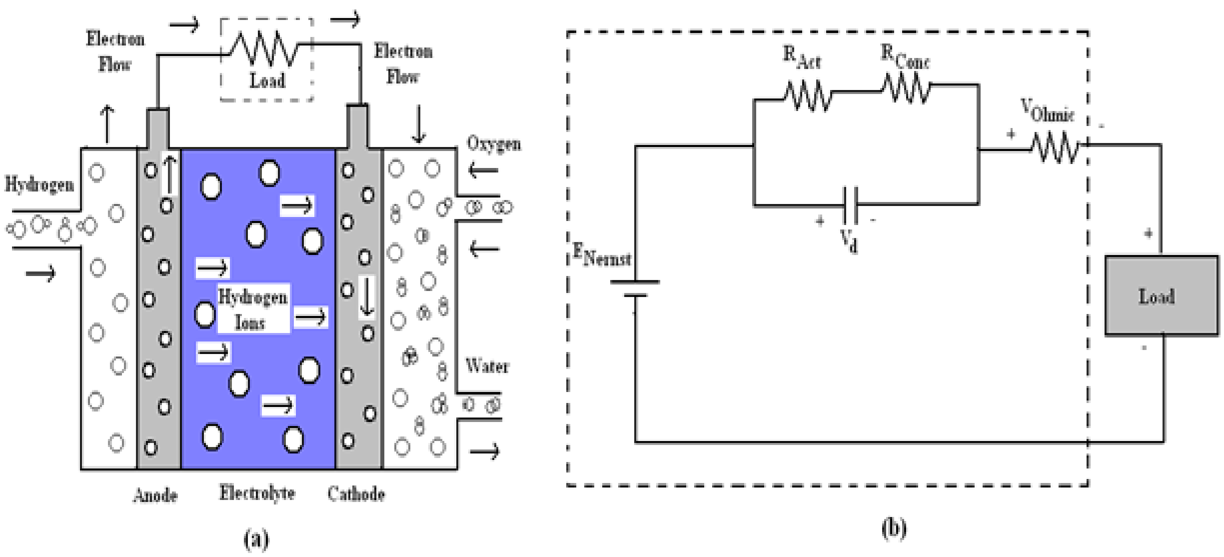


Fig 1.Overall Configuration of Proposed system

3. Fuel Cell

In this paper a Proton exchange membrane fuel cell (PEMFC) is used which delivers a high power in the range of kilo watts for long duration. A 45 V DC six kilowatt 6.5 Ah fuel cell is modeled in MATLAB/Simulink to apply fuel cell as a hybrid source for our electrical vehicle system. Schematic diagram of a fuel cell and an electrical equivalent circuit of a PEM fuel cell is given in fig 2. The output voltage obtained from a single fuel cell is given in equation (1) and if number of cells is stacked and its voltage relation is given in equation (2). Equation (3-7) describes the V-I characteristics [13] a fuel cell and its polarization effects.

Issn No:0975-0932



Fg.2. (a) Schematic Diagram (b) Electrical Circuit of PEM fuel cell

$$V_{Fuel} = E_{Nernst} - V_{act} - V_{ohmic} - V_{conc} \tag{1}$$

$$V_{stack} = N \times V_{Fuel} \tag{2}$$

$$E_{Nernst} = 1.229 - 8.5 \times 10^{-4} (T - 29815) + 4.318 \times 10^{-5} T \left[\ln \left(P_{H_2} + \frac{1}{2} \ln P_{O_2} \right) \right] \tag{3}$$

$$V_{Act} = \xi_1 + \xi_2 T + \xi_3 T \ln(CO_2) + \xi_4 T \ln(I) \tag{4}$$

$$CO_2 = \frac{P_{O_2}}{5.08 \times 10^6 \exp\left(-498/T\right)} \tag{5}$$

$V_{ohmic} = I$ (Remembrance)

Here, Remembrance $= \dfrac{r_m^{l}}{A}$

$$r_m = \frac{181.6\left[1+0.03\left(\frac{I}{A}\right)+0.062\left(\frac{T}{303}\right)^2\left(\frac{I}{A}\right)^{2.5}\right]}{\left[\lambda-0.634-3\left(\frac{I}{A}\right)\right]\exp\left[4.18\left(\frac{T-303}{T}\right)\right]} \quad (6)$$

$$V_{con} = \xi_6 e^{(\xi_7 I)} \quad (7)$$

4. Mathematical Model of PMSM

The mathematical equations of PMSM motors stator current in a dq synchronously rotating frame is given by

$$\frac{d}{dt} i_q = \frac{1}{L_q}\left(v_q - R i_q - \omega_e \phi_d\right) \quad (8)$$

$$\frac{d}{dt} i_d = \frac{1}{L_d}\left(v_d - R i_d - \omega_e \phi_q\right) \quad (9)$$

$$\phi_d = \phi_f + L_d i_d \quad (10)$$

$$\phi_q = L_q i_q \quad (11)$$

Torque developed from a PMSM motor is given by

$$T_m = \frac{3}{2} P\left(i_q \phi_d - i_d \phi_q\right) \quad (12)$$

Where v_q *and* v_d are stator voltages in dq frame, i_q *and* i_d are stator currents in dq frame, L_q *and* L_d are motor inductances in dq frame, ϕ_d *and* ϕ_q are flux of PMSM motor in dq frame, T_m is electro-magnetic torque developed by PMSM motor.

5. Model predictive Controller for PMSM

Following equations are used to generate voltage control signal for inverter driving PMSM motor [14]. It is based on predictive control over stator currents which helps to improve the torque profile of motor. The predictive current vector is given by

$$i_{\widehat{k+1}} = i_k + T\left(F_k I_k + D_k + L_0^{-1} V_k - \frac{1}{T} K_\eta \eta_k\right) \quad (13)$$

Issn No:0975-0932

$$\widehat{e_k} = i_k - \widehat{i_k} \quad (14)$$

Equation (15) gives the voltage control signal output from predictive current controller

$$v_k = -L_0\left[F_k\widehat{i_k} + d_k - \frac{1}{T}\left(i^* - \widehat{i_k} + K_\eta + \widehat{e_0} + \cdots + \widehat{e_{k+1}}\right)\right] \quad (15)$$

But,

$$i^* - \widehat{i_k} = e_k + \widehat{e_k} \quad (16)$$

Hence (15) can be written as follows

$$v_k = -L_0\left[F_k\widehat{i_k} + d_k - \frac{1}{T}\left(e_k - \left(K_\eta - I_2\right)\widehat{e_k} + K_\eta \eta_k\right)\right] \quad (17)$$

$$e_{k+1} = \left(K_\eta - I_2 - TF_k\right)\widehat{e_k} - K_\eta \eta_k - T\phi_k \quad (18)$$

$$\widehat{e_{k+1}} = K_\eta \eta_k + T\phi_k \quad (19)$$

$$\eta_{k+1} = \eta_k + \widehat{e_{k+1}} \quad (20)$$

6. Simulation Results and Discussions

PMSM motor based proposed electrical vehicle system containing hybrid sources (battery and fuel cell) is simulated in MATLAB/Simulink software and results are presented in this section. Parameters applied during simulation is given in Table I, It contains PMSM motor parameters, fuel cell specifications and buck boost converter circuit parameters. Overall MATLAB Implementation of proposed PMSM drive for Electric Vehicle Applications is shown in figure 3. Performance of battery is shown in figure 4 and output voltage of fuel cell is shown in figure 5. A buck boost converter is employed to boost the hybrid source input voltage to the level required for motor ratings and the corresponding DC link voltage is shown in figure 6. Model based predictive current controller is utilized for improving the torque and current profile of the PMSM motor and the motors performance such as phase voltage, speed response, electro-magnetic torque response and stator current response are shown from figure 7 to 10.

TABLE 1 SIMULATION PARAMETERS

PMSM MOTOR PARAMETERS	
Name	Range
Rated Power	5 hp

Issn No:0975-0932

Rated Speed	1500 rpm
Rated Voltage	310 V
Stator Resistance (Rs)	0.7 ohms
Stator Inductance (Ls)	2.72mH
Poles	4
Torque Constant	0.235N.m/A
Flux Linkage	0.175 V.s
Fuel Cell SPECIFICATIONS	
Voltage	45V
Current	6.5A
Power	6KW
Buck Boost Converter PARAMETERS	
Inductors (L_1, L_2)	0.1mH, 2mH
Capacitors(C_1, C_2)	1000μF
DC-Link Voltage (V_{DC})	310V

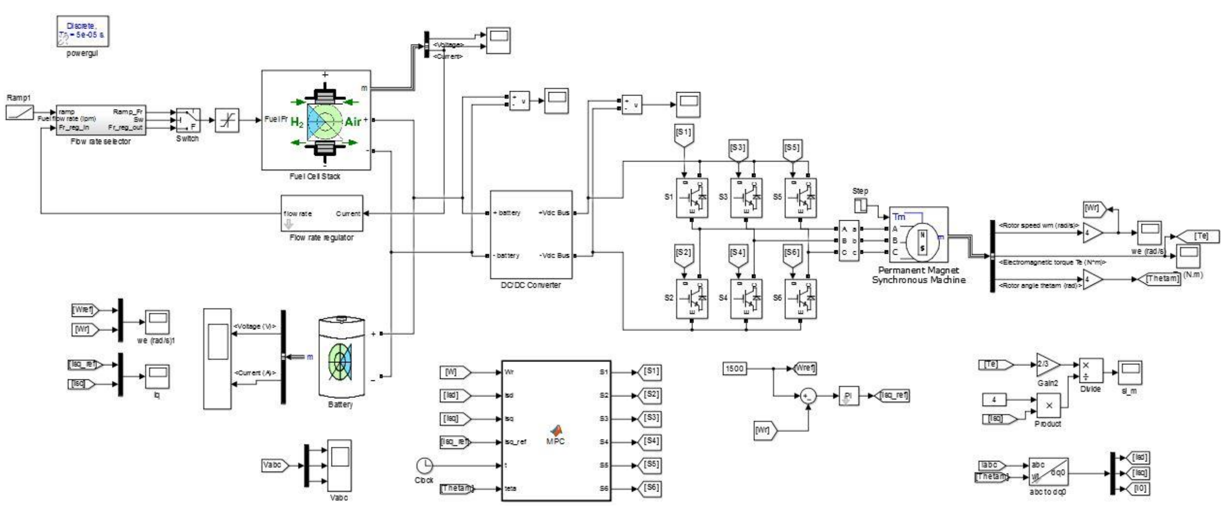


Fig 3.Matlab Implementation of proposed PMSM drive for Electric Vehicle Applications

Issn No:0975-0932

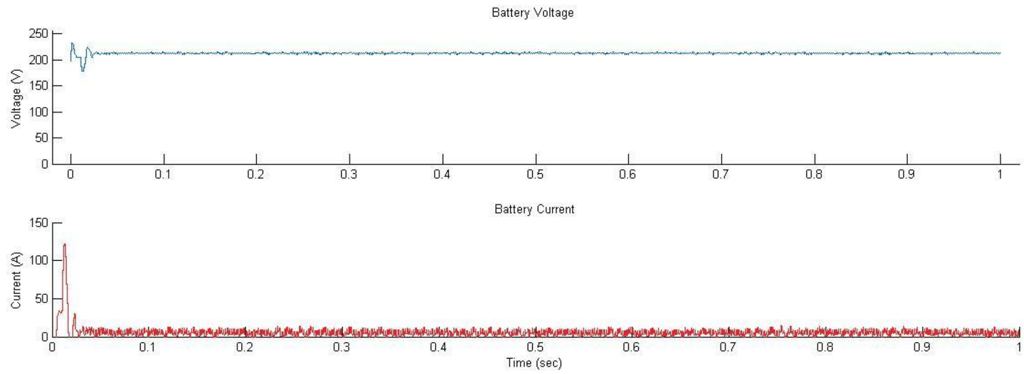


Fig 4.Battery (A).Output Voltage (B).Output Current

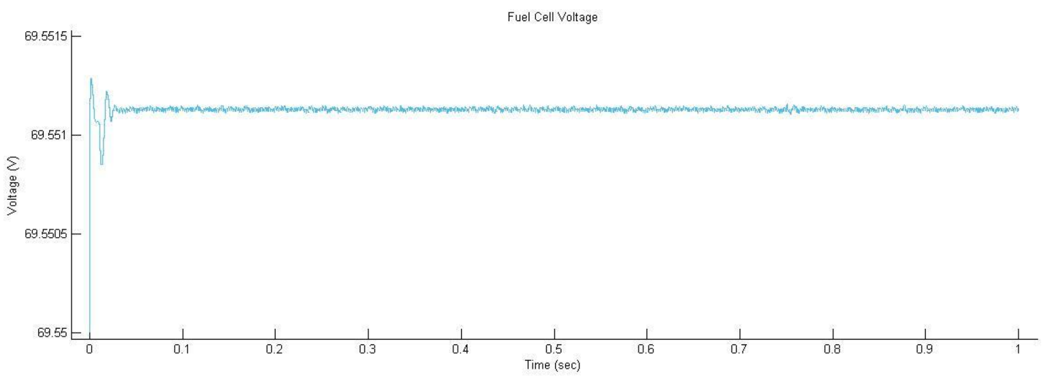


Fig 5.Fuel Cell output voltage waveform

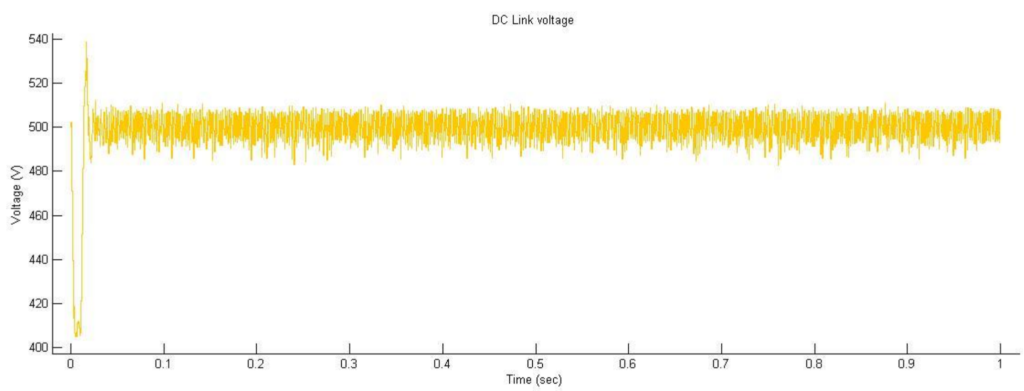


Fig 6.DC link voltage waveform

Issn No:0975-0932

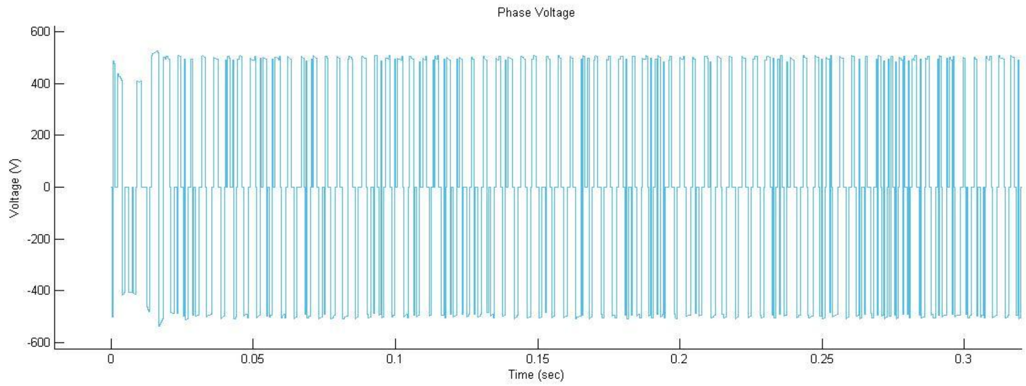


Fig 7.R phase output voltage waveform

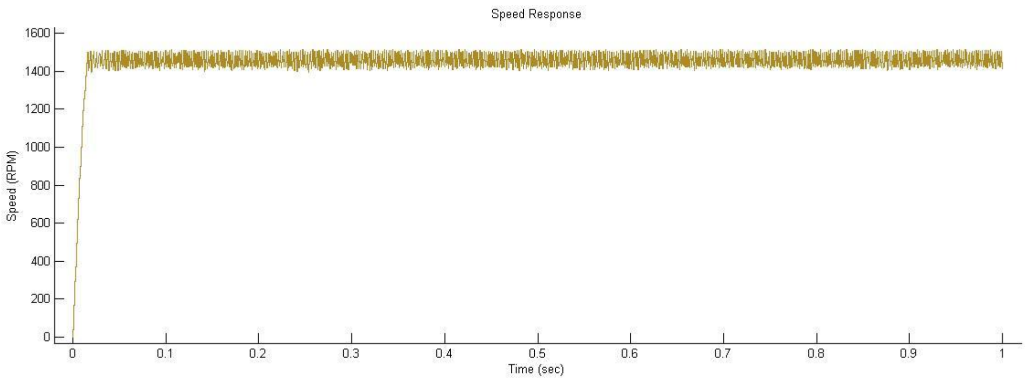
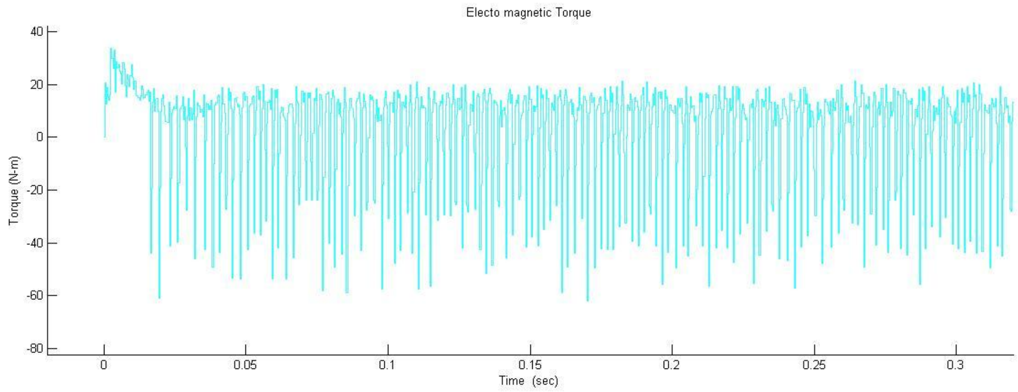


Fig 8.Speed response of PMSM motor



Issn No:0975-0932

Fig 9.Torque response of PMSM motor

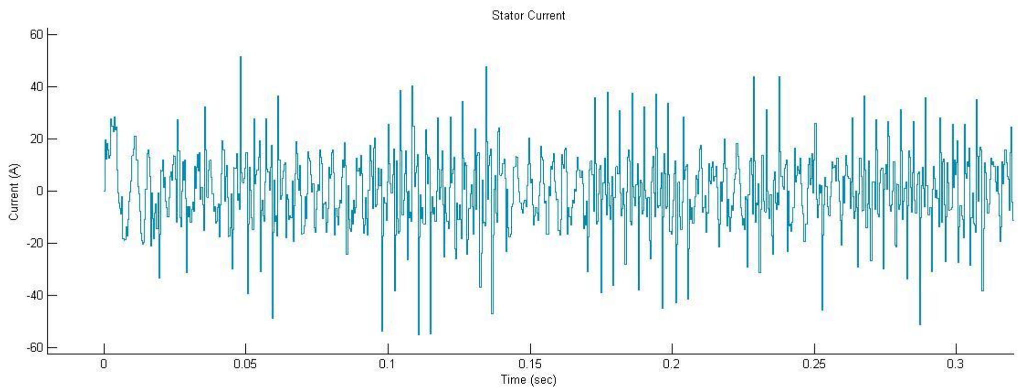


Fig 10.Stator current response of PMSM motor

7. Conclusion

This paper presented a model predictive current controller for PMSM drive powered through hybrid battery and fuel cell sourced electrical vehicle. Advantage of a MPC controller is it can predict the future changes in the system based on past and present inputs and improves the dynamic performance of the system. MPC controller enhances the overall efficiency of the proposed system by ensuring precise control over output current from the drive. A buck-boost converter is employed to provide optimum dc link performance required for the voltage source inverter fed PMSM motor. The major use of the buck boost converter is to boost the voltage available from battery and fuel cell even during low state of charge regions for stable operation of the drive. The performance of proposed conversion and control system for PMSM drive is verified through simulations using electrical vehicle model was developed in MATLAB/Simulink environment.

References

[1]. Kwangsoo Kim, Jaenam Bae, Won Ho Kim, Sang-Hwan Ham, Suyeon Cho and Ju Lee, "Design and comparison between IM and PMSM for hybrid electrical vehicles," *Digests of*

Issn No:0975-0932

the 2010 14th Biennial IEEE Conference on Electromagnetic Field Computation, Chicago, IL, 2010, pp. 1-1.

[2]. A. M. Omara and M. A. Sleptsov, "Performance assessment of battery-powered electric vehicle employing PMSM powertrain system," *2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, St. Petersburg, 2017, pp. 963-968.

[3]. L. Sepulchre, M. Fadel, M. Pietrzak-David and G. Porte, "Flux-weakening strategy for high speed PMSM for vehicle application," *2016 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, Toulouse, 2016, pp. 1-7.

[4]. R. Mocanu and A. Onea, "Passivity Based Torque Control of PMSM used in electrical vehicles," *2015 19th International Conference on System Theory, Control and Computing (ICSTCC)*, Cheile Gradistei, 2015, pp. 803-810.

[5]. R. Mocanu and A. Onea, "Phase resistance estimation and monitoring of PMSM used in electrical vehicles," *2014 18th International Conference on System Theory, Control and Computing (ICSTCC)*, Sinaia, 2014, pp. 512-519.

[6]. Zhang Jian, Wen Xuhui and Zeng Lili, "Optimal system efficiency operation of dual PMSM motor drive for fuel cell vehicles propulsion," *2009 IEEE 6th International Power Electronics and Motion Control Conference*, Wuhan, 2009, pp. 1889-1892.

[7]. P. Pany, R. K. Singh and R. K. Tripathi, "Performance analysis of fuel cell and battery fed PMSM drive for electric vehicle application," *2012 2nd International Conference on Power, Control and Embedded Systems*, Allahabad, 2012, pp. 1-7.

[8]. A. K. Gautam, S. P. Singh, J. P. Pandey and T. N. Shukla, "Performance investigation of Permanent Magnet Synchronous Motor (PMSM) drive supplied from hybrid sources," *2016 International Conference on Emerging Trends in Electrical Electronics & Sustainable Energy Systems (ICETEESES)*, Sultanpur, 2016, pp. 292-302.

[9]. A. Ayad, P. Karamanakos, R. Kennel and J. Rodríguez, "Direct model predictive control of bidirectional quasi-Z-source inverters fed PMSM drives," *2017 11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, Cadiz, 2017, pp. 671-676.

[10]. A. A. Ahmed, Jung-Su Kim and Y. I. Lee, "Model predictive torque control of PMSM for EV drives: A comparative study of finite control set and predictive dead-beat control schemes," *2016 Eighteenth International Middle East Power Systems Conference (MEPCON)*, Cairo, 2016, pp. 156-163.

[11]. V. Šmídl, Š. Janouš and Z. Peroutka, "Extending horizon of finite control set MPC of PMSM drive with input LC filter using LQ lookahead," *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, TX, 2014, pp. 581-586.

Issn No:0975-0932

[12]. V. Muzikova, T. Glasberger, V. Smidl and Z. Peroutka, "Finite control set MPC with high frequency injections for sensor less position and speed estimation of a PMSM," *2015 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)*, Valparaiso, 2015, pp. 9-14.

[13]. J. G. Lee, J. W. Ahn, S. y. Choe and S. H. Baek, "Integrated modeling and simulation of a PEM fuel cell system for active and reactive power compensation," *2006 37th IEEE Power Electronics Specialists Conference*, Jeju, 2006, pp. 1-8.

[14]. T. Türker, U. Buyukkeles and A. F. Bakan, "A Robust Predictive Current Controller for PMSM Drives," in IEEE Transactions on Industrial Electronics, vol. 63, no. 6, pp. 3906-3914, June 2016.

Issn No:0975-0932