Constraints Reduced on the PEM Fuel Cell in Hybrid Electric Vehicle Application by using Multilevel Inverters

Hassina ABDELLAOUI[1], Kaci GHEDAMSI[2], Amar MECHAREK[1]

[1]Faculty of Electrical and Computer Engineering, Mouloud Mammeri University of Tizi-Ouzou
[2]Laboratory of Renewable Energies Mastery, Faculty of Technology, University of Bejaia

E-mail : hassinaabdellaoui@yahoo.fr

Abstract - Fuel cell/Ultracapacitor (FC/UC) hybrid power source forms a promising architecture to satisfy the energy requirements for electrical vehicles. When the main power source is a fuel cell, the objective is to increase its utilization by improving their performance and ensure continuous operation during the failure of any semiconductors. The fluctuating load can cause unstable operation as well as low efficiency. Multilevel inverters offer the best solution for improving the power quality of the traction motor (load) with fewer harmonics and ensuring continuity of operation in the event of a switch failure. In this paper, the load constraints on the FC are reduced by using multilevel inverters. The objective is to enhance the power quality of traction motor without any additional device and ensure continuity of operation in the event of a fault in semiconductors. We analyze the opportunities of using a seven-level inverter in an electric powered vehicle. The results obtained show the effectiveness by using multilevel inverters in improving the power quality, enhancing the fuel cell performance and ensure a long lifetime of hybrid electric vehicle (HEV) systems.

Keywords - Fuel Cell, Hybrid Electric Vehicle, Multilevel Inverter.

I. INTRODUCTION

Nowadays, the increasing worldwide use of automobiles is again heavily dependent on fossil fuels and is the main cause of the concentration of CO_2 in the atmosphere, contributing to global warming, rising sea levels and increasing greenhouse gas emissions levels in the atmosphere [1].

An interesting alternative source to produce near zero emission of polluting gases in a hybrid electric vehicle is the fuel cell system [2]. For this reason, fuel cell technology has been advanced as a zero-emissions concept and one representation of numerous clean energy technologies, because it possesses many advantages such as high energy density and autonomy, no pollution, light weight, easy manufacturing and so on, there is a trend for more and more research based on the development of fuel cell technology [3-4]. Therefore, the recent traction drive system of HEV consists of a FC stack, an ultracapacitor, power electronic circuit, and a traction motor. The hybrid input power is used to drive the electric motor associated with the vehicle dynamics and the resources of power electronics is used at various junctures for optimal energy management of the HEV. Fluctuating loads consists an important part of the power consumed in many applications. For automotive applications, they generate peaks reaching more than ten times the power average pmoy of the load, which generates a very restrictive dynamic. For this, multilevel inverters can be employed in the HEV to feed the traction motor. It is an effective and practical solution for enhancing power demand quality and reducing harmonics of ac waveforms [5-6]. The output waveform has more steps as the number of levels increases; this makes it possible to produce a stepped wave that is close to the desired waveform [7]. Several configurations or topologies of inverters are studied whose objective is to find the ideal structure for an application type electrical vehicle (EV) [8-9]. Nowadays, The NPC inverter has been most widely used for application of high (or medium) voltage and high-power drives, because with the same ratings of the device, the voltage across each switching power device is half fraction of the conventional two-level inverter [10].

Currently, many authors interest on the use of multilevel inverters for HEV. In [7], the IGBT based cascaded multilevel has been developed and it is interfaced with 20 kW 3-phase induction motors that proved to be suitable for HEVs. The references [5-11] proposed the use of different level cascaded inverters to feed the traction motor in electric drive. It is found that the cascaded multilevel inverters are proper for medium-voltage, high-power application; they reduce harmonics and produce sinusoidal voltages. However, based on their configurations, they are limited by the need of separate DC sources and they are more complicated than other types of converters. Therefore, in diode-clamped converters, it is easy to extend the voltage to higher levels. In addition, diode clamped converters are mainly used in low and medium-power applications [12]. In order to offer redundancy to the power switches, a Scott transformer topology is presented in an Integrated Power Module (IPM) [13] and a fault-tolerant scheme is simulated to test the PMSM operation in a plug-in hybrid electric vehicle (PHEV).

In this paper, we propose to improve the fuel cell performances and increase its lifetime by using a Neutral-Point Clamped (NPC) seven-level inverter. This multilevel is used to feed a traction motor, which is in our system a permanent magnet synchronous machine (PMSM). These multilevel inverters allow to get a better power quality with lower value of THD (total harmonic distortion) and able to sustain the operating performance of the speed of HEV in fault-tolerant mode.

The energy management with fuzzy logic is given. The simulation results are compared to the conventional two-level inverter.

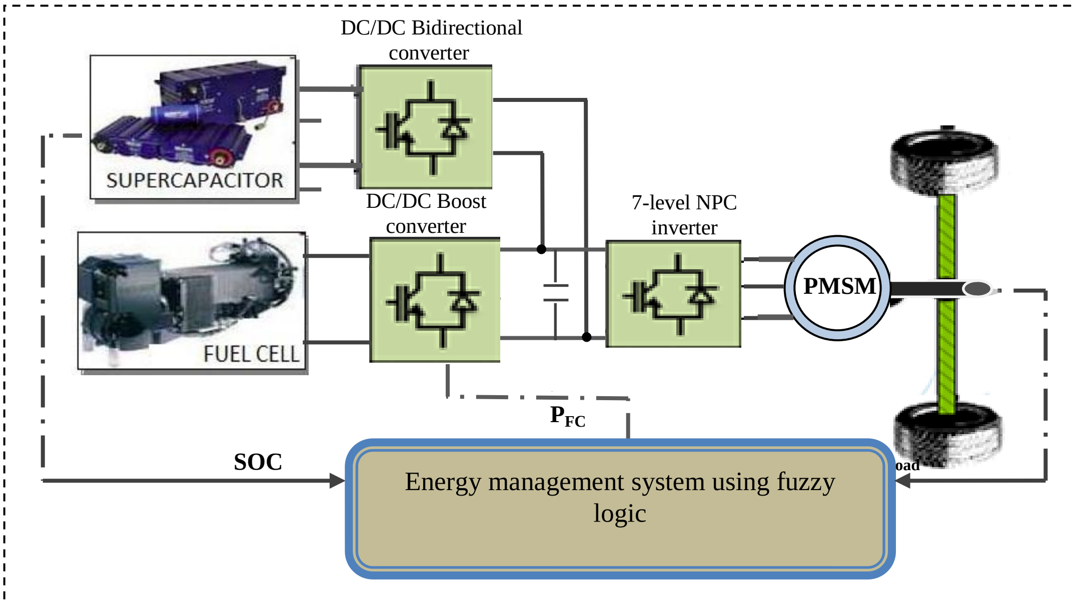

Fig.1. FC/UC hybrid electric vehicle topology.

II. SYSTEM DESCRIPTION

The global system is detailed in Fig. 1. It is composed of two sources: the fuel cell and the ultracapacitor, which are connected to the DC link bus via a unidirectional DC/DC and a current bidirectional DC/DC converters respectively. The FC/UC currents are controlled using PI regulator and the DC link voltage is chosen to be maintained to 500V to supply the traction motor (PMSM) with employing of a seven-level inverter to convert the DC voltage on AC voltage. The energy management of hybrid source based on fuzzy logic is used in the whole vehicle cycle. Simulations are obtained using MATLAB/Simulink under various operating conditions to show the effectiveness of proposed methodology. Simulation results reflect the effectiveness of proposed scheme in different operating conditions (steady state and dynamic).

III. SEVEN-LEVEL NPC INVERTER MODELING

A three phase seven-level NPC inverter is given in Fig.2.

The seven-level NPC inverter presented in Fig 3, consists of six capacitors, C_1, C_2, C_3, C_4, C_5 and C_6. Each capacitor is crossed by a voltage of $V_{dc}/6$.

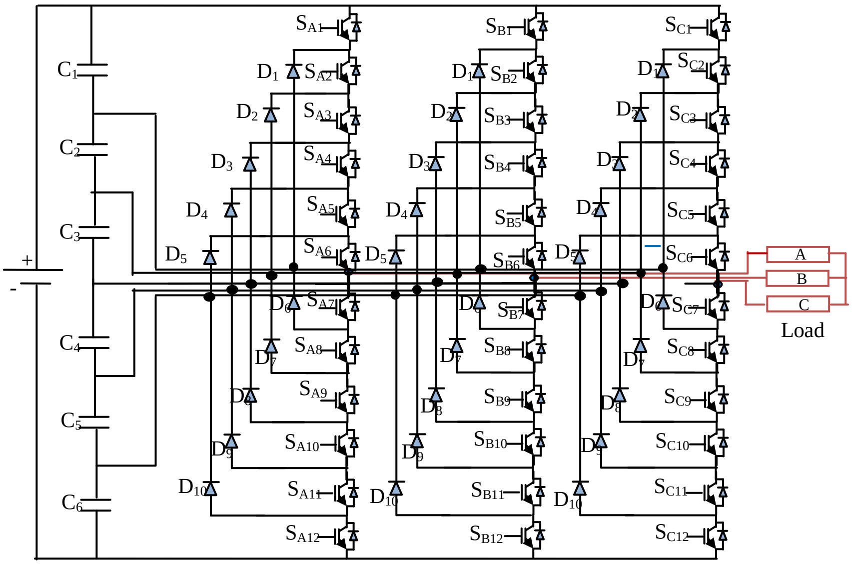

Fig.2. Structure of the Three-phase seven-level NPC inverter.

Table 1 shows how the staircase voltage is synthesized. In order to explain how the staircase voltage is synthesized, we consider the neutral point n as the output phase voltage reference point [14].

Table 1. Switching states for a seven level NPC inverter.

V_0	$V_{dc}/2$	$V_{dc}/3$	$V_{dc}/6$	0	$V_{dc}/6$	$V_{dc}/3$	$V_{dc}/2$
S_1	1	0	0	0	0	0	0
S_2	1	1	0	0	0	0	0
S_3	1	1	1	0	0	0	0
S_4	1	1	1	1	0	0	0
S_5	1	1	1	1	1	0	0
S_6	1	1	1	1	1	1	0
S_7	0	1	1	1	1	1	1
S_8	0	0	1	1	1	1	1
S_9	0	0	0	1	1	1	1
S_{10}	0	0	0	0	1	1	1
S_{11}	0	0	0	0	0	1	1
S_{12}	0	0	0	0	0	0	1

IV. VEHICLE MODELING

The different forces acting the vehicle are: the traction forces F_t caused by the action of the two drive wheels, the friction force to the advancement F_{roll}, the effort of aerodynamic resistance F_{aero} and the resistance of mounted side F_{slope} [15-16]. The resisting forces are given by the following equations :

$$F_{roll} = M_v\, g\, f_r \quad (1)$$

$$F_{aero} = \frac{1}{2}\rho A C_X V_v^2 \quad (2)$$

$$F_{slope} = M_v\, g \sin(\delta) \quad (3)$$

The fundamental principle of the vehicle dynamics is described by the following equation:

$$M_v \frac{dV_v}{dt} = F_t - F_{roll} - F_{aero} - F_{slope} \quad (4)$$

The parameters of the HEV model are given in Table 4.

V. CONTROL SYSTEM AND REGULATION

A) Speed Regulation and Inverter control of PMSM

Using the sliding mode control, the objective is to force the system dynamics to match the sliding surface *S(x)* by the following equation command:

$$U = U_{eq} + U_n \quad (5)$$

With: *U* - control variable *Ueq* - size equivalent command, *Un*- size discontinuous control.

$$U_n = K\,\mathrm{sign}(S(x)) \quad (6)$$

With : K is a positive gain

So that the surface is attractive, the regulator sliding mode should be selected so that the function satisfies the criterion of Lyapunov stability [17-18] :

$$S(x)\,\dot{S}(x) \leq 0 \quad (7)$$

The sliding surface is defined by:

$$S(\Omega) = \Omega_{ref} - \Omega \quad (8)$$

The derivative of this surface may be expressed as :

$$\dot{S}(\Omega) = -C_1\Omega + \frac{C_r}{J} + \Omega_{ref} - (c_2 I_{ds} + c_3) I_{qs} \quad (9)$$

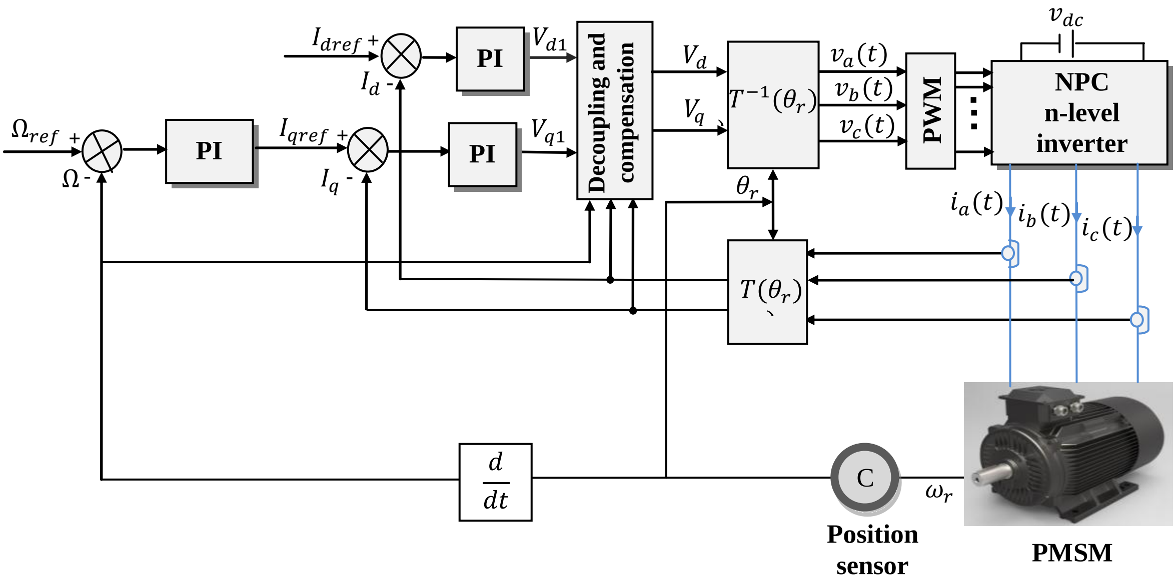

Fig. 3. PMSM vector control.

The figure 3 shows the vector control of the PMSM

B) UC converter control and DC bus voltage regulation

The control strategy of bidirectional converter is shown in fig. 4.

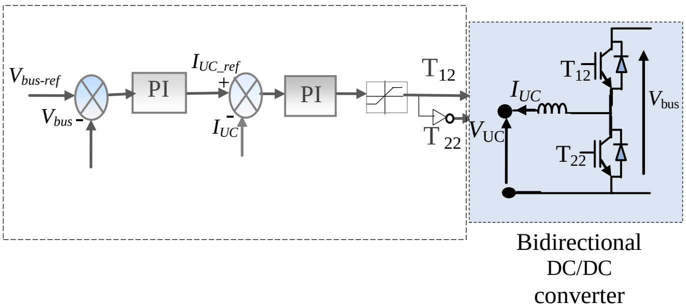

Fig. 4. UC converter control and DC bus voltage regulation

C) FC converter control

Fig. 5 shows a boost DC/DC converter and fuel cell current regulation.

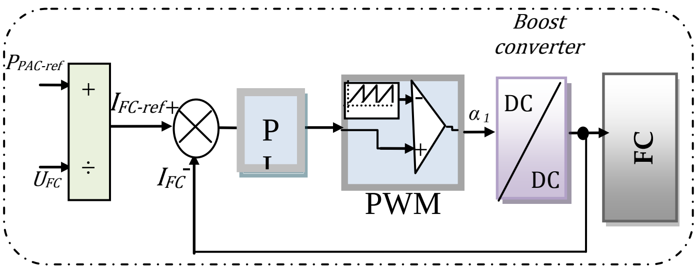

Fig. 5. Fuel Cell converter control.

D) Energy management using fuzzy logic

In HEV, fuzzy logic is widely employed in many applications [19]. Fuzzy control system is a control method which is applied with great success in various control applications. It is used for nonlinear systems that represent a difficulty in the deriving of its mathematical model. The energy management strategy using fuzzy logic (Fig.6) coordinates all the elements in the system to continuously provide the necessary traction, to keep constant the DC bus voltage (V_{bus}) and maintain the UC SOC (state-of-charge).

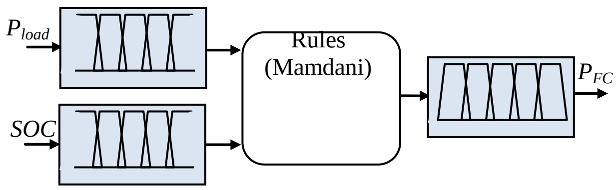

Fig. 6. Energy management using fuzzy logic.

The inputs of FLC (Fuzzy logic control) are: The load power (P_{load}) and ultracapacitor SOC, and the output of the FLC is the fuel cell power (P_{FC})

VI. SIMULATION RESULTS AND INTERPRETATION

To validate the proposed work, simulation studies have been realized by using MATLAB/SIMULINK**.** The results have been done using a new european driving cycle (NEDC) of 1200 seconds and with 120 km/h maximum speed as shown in Fig. 7.

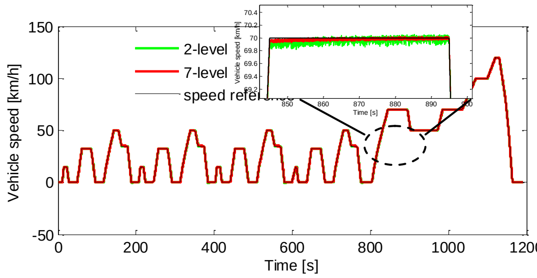

Fig. 7. Speed vehicle during the proposed cycle.

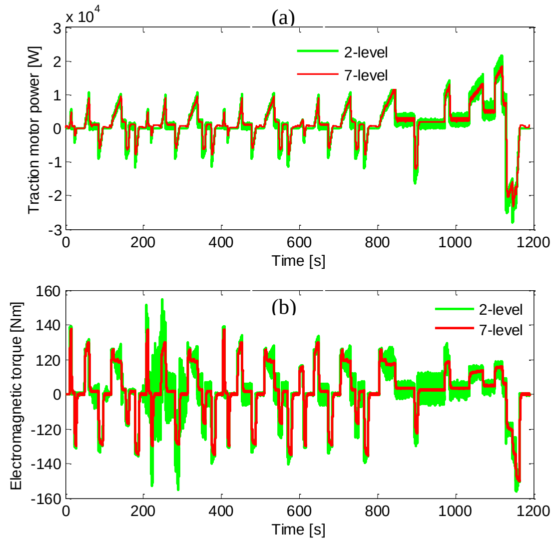

Fig. 8. (a) Traction motor power; (b) Electromagnetic torque.

Table 2. Comparison of voltage THD and current THD between the two inverter configurations.

Inverter Configuration	THD (%)	
	Voltage	current
Two-level Inverter	69.87%	30.25%
Seven-level Inverter	20.09%	16.7%

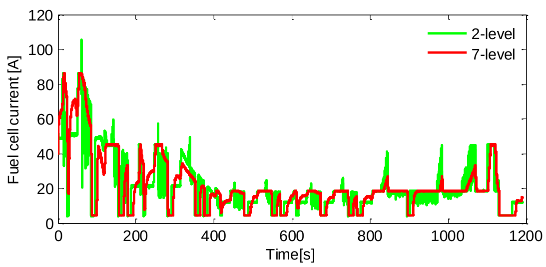

Fig. 9. Fuel cell current.

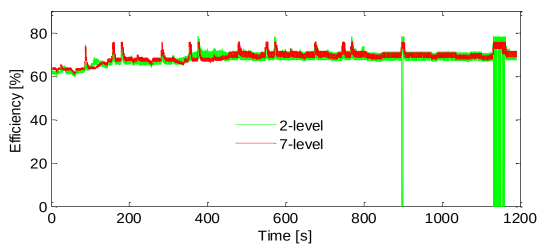

Fig. 10. Fuel cell efficiency.

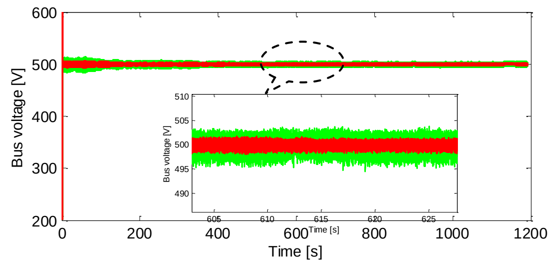

Fig. 11. DC Bus voltage.

The speed of the vehicle follows the reference speed as shown in Fig. 7, but with the use of a multilevel inverter, the speed is smoother compared to that obtained with the two-level inverter.

Fig. 8 shows the power and the electromagnetic torque of PMSM. It is seen that the electrical and mechanical performance of traction motor are appreciably improved using 7-level inverter. Current and voltage THD (Table 2) are greatly decreased with the multilevel inverter.

The fuel cell current is shown in Fig. 9, we can remark from these results that the load fluctuations are eliminated in the case of using a multilevel inverter. The quality of the power is improved and the efficiency of the fuel cell, as shown in Fig. 10, is improved.

The DC bus voltage fellows the reference which is fixed to 500V (fig.11), and with the use of seven-level inverter, the DC bus voltage is better.

VII. CONCLUSION

Our main objective of this work was the reduction of the load constraints on the fuel cell. Since the characteristics of the fuel cell depend heavily on the load, multilevel inverter was the right solution to improve the performance of the traction motor.

The studied system was composed of a hybrid source (FC/UC), converters, and traction motor (PMSM) which is supplied by a NPC 7-level inverter. The fuzzy logic method is applied for the energy management of this system.

The different simulation results obtained, showed the interest of using a 7-level inverter in HEVs by improving the performance of the load, enhancing the quality of the power, decreasing of the electromagnetic torque ripple and the reduction of the current and the voltage THD's. This allowed reducing the load constraints on the fuel cell and improving its characteristics and performance. This has made it possible to improve the quality of the power of the ultracapacitor and of the bus voltage.

Therefore, from this study, it can be concluded that the use of a multi-levels NPC inverter for HEV gives satisfactory results in terms of system performance and ensures continuity of service in the event of semiconductor failure.

VIII. APPRENDIX

Table 3. Fuel cell parameters

	Symbol	Values
Nominal power	$P_{FC,nom}$	35 kW
Internal resistance	R_{FC}	3 mΩ
Activation over voltage constant	B	0.0477 V
Hydrogen valve constant	K_{H2}	$4.22.10^{-5}$k.mol.atm/s
Oxygen valve constant	K_{O2}	$4.22.10^{-5}$k.mol.atm/s
Temperature	T	65 °C

Table 4. Ultracapacitor parameters

	Symbol	Values
Capacity	F	500 F
Resistance	R_{UC}	2.4 mΩ
Voltage	V_{UC}	16.2 V
Maximal power	$P_{UC,max}$	40 kW

Table 5. Vehicle parameters

	Symbol	Values
Vehicle total mass	M_v	800 kg
Front total surface area of the vehicle	A_f	1.75 m^2
Rolling resistance coefficient	C_r	0.009
Air density	ρ_{air}	1.2 kg/m^3
Acceleration due to gravity	g	9.81m/s^2

IX. REFERENCES

[1] G. Napoli, S. Micari, G. Dispenza, S. Di Novo, V. Antonucci and L. Andaloro, Development of a fuel cell hybrid electric powertrain: A real case study on a Minibus application. *International Journal of Hydrogen Energy, 42 (46)*, 2017, 28034-28047.

[2] K. Ettihir, M. Higuita Cano, L. Boulon and K. Agbossou, Design of an adaptive EMS for fuel cell vehicles, *International Journal of Hydrogen Energy, 42(2)*, 2017, 1481-1489.

[3] C. Wang and M. Hashem Nehrir, Load transient mitigation for standalone fuel cell power generation systems. *IEEE Trans Energy Conversion, 22 (4)*, 2007, 864 – 872.

[4] L. Jianxing, S. Laghrouche, A. Fayez-Shakil and M. Wack, PEM fuel cell air-feed system observer design for automotive applications. An adaptive numerical differentiation approach, *Inernational Journal of Hydrogen energy, 39 (30)*, 2014, 17210-17221.

[5] R. Bhavani and G. Swapna, Multilevel inverter for higher output voltage levels. *International Journal for Research in applied acience & angineering aechnology (IJRASET), 4 (7)*, 2014, 506-515.

[6] S. Prachi, N. Sandeep, P.S. Kulkarni and R.Y. Udaykumar. A Comparison of seven-level inverter topologies for multilevel DC-AC power conversion. *International conference on power electronics, drives and energy systems (PEDES)*, 16-19 December 2014, 4799-6373.

[7] A.K. Verma, P.R. Thakura, K.C. Jana and G. Buja. Cascaded multilevel inverter for hybrid electric vehicles. *India International Conference on power electronics (iicpe)*, 28-30 January 2011, 1 – 6.

[8] M. Fatemeh and K. Abbas. A preliminary study for improving reliability in hybrid vehicles. *Procedia computer science*, *42*, 2014, 308–312.

[9] P. Barriuso, J. Dixon, P. Flores and L. Moran. Fault tolerant reconfiguration system asymmetric multilevel converters using bi-directional power switches. *IEEE transactions on industrial electronics, 56 (4), 2009,* 1300 – 1306.

[10] P. Je-Jong; K. Tae-Jin and H. Dong-Seok. Study of neutral point potential variation for three-level NPC inverter under fault condition. *Industrial electronics (IECON), 34th annual conference of IEEE* , 2008, 983 – 988.

[11] F. Khoucha, S. M. Lagoun, Kh. Marouani, A. Kheloui and M. Ben-bouzid. Hybrid cascaded h-bridge multilevel inverter motor drive DTC control for electric vehicles. *Proceedings of the International Conference on electrical machines*, 2008.

[12] S.M. Mousavi, S. Hamidifar and C. Narayan. A novel bidirectional DC/AC stacked matrix converter design for electrified. *IEEE Transactions on vehicular technology*, 63(7), 2014, 3038-3050.

[13] T.D. Mai, Ch. Yonghua, D.Y. Johan. Fault-tolerant operation of power converters in phevs coupled by a scott transformer. *38th annual Conference of the IEEE industrial electronics society (IECON) Canada*, 2012, 4258- 4263.

[14] P. Sanoop and Ch. Vinita. Seven level inverter topologies: A comparative study. *International Journal of Innovative research in Electrical, Electronics, Instrumentation and Control Engineering (IJIREEICE)*, 3(1), 2016, 148-162.

[15] P. Alireza, P. Serge and T.F. Meibody. Energy control of super capacitor/fuel cell hybrid power source. *International Journal of Energy conversion and management*, 49(6), 2008, 1637-1644.

[16] H. Jenn-Jiang, Jie-Ch Yu and K. Jenn-Kun. The study on the power management system in a fuel cell hybrid vehicle. *International Journal of Hydrogen energy; 37(5), 2012,* 4476-4489.

[17] D. Lindita and A. Spahiu. An improved performance of sensorless PMSM drive control with sliding mode observer in low speed operation. *International Journal of Engineering Trends and Technology (IJETT)*, 4(5), 2013, 2231-5381.

[18] M. Reichhartinger, M. Horn. Sliding-mode control of a permanent magnet synchronous motor with uncertainty estimation. *International Journal of Electrical and computer engineering*, 4 (11), 2010.

[19] I. Abadlia, T. Bahi and H. Bouzeria. Energy management strategy based on fuzzy logic for compound RES/ESS used in stand-alone application. *International Journal of Hydrogen Energy*, 41(38), 2016, 16705-16717.