

# Performance and Lifetime Increase of the PEM Fuel Cell in Hybrid Electric Vehicle Application by Using an NPC Seven-level Inverter

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https://doi.org/10.18280/jesa.520314	ABSTRACT
Received: 13 March 2019 Accepted: 29 May 2019	The objective of this study is to enhance the PEM fuel cell performances and increase its lifetime by using a Neutral-Point Clamped (NPC) seven-level inverter without any additional
<i>Keywords:</i> <i>PMSM, ultracapacitor, multilevel</i> <i>inverter, sliding mode control, fuzzy logic</i> <i>control</i>	device in Hybrid Electric Vehicle (HEV) application. The multilevel inverter is used to feed a traction motor, which is in our system a permanent magnet synchronous machine (PMSM) of a hybrid electric vehicle. The energy management of the hybrid source (Fuel cell/ultracapacitor) using fuzzy logic is given and the vehicle speed is controlled by using the sliding mode control. The simulation results are compared to the conventional two-level inverter. Through this study, it was found that the use of seven-level inverter improve the power quality of traction motor, decrease the value of current and voltage THD (total harmonic distortion), reduce the constraint of the fuel cell, improve its efficiency and ensure length lifetime of hybrid electric vehicle (HEV) system. The main contribution of this paper is to show the advantages of using a seven-level inverter to increase the performance and lifetime of fuel cell in HEV application.

# **1. INTRODUCTION**

With climate change becoming of increasing concern in recent years, vast global efforts have focused on producing renewable energy sources and reducing greenhouse gas emissions [1]. An interesting solution to produce near zero local emission electricity in an embedded system (as hybrid vehicle) is the fuel cell system [2]. The fuel cell technology is one representation of numerous clean energy technologies, because it possesses many advantages such as no pollution, high energy density, light weight, easy manufacturing, safety and so on, there is a trend for more and more research focusing 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 are used at various junctures for optimal energy management of the HEV. Fluctuating loads consist an important part of the power consumed in many applications. For automotive applications, they generate peaks reaching approximately more than ten times the power average  $p_{moy}$  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 increasing power demand quality and reducing harmonics of ac waveforms [5-6]. As the number of levels increases, the synthesized output waveform has more steps, which produces a staircase wave that approaches in a desired waveform [7].

Many configurations or topologies of power converters are proposed whose objective is to find the ideal structure for an application type electrical vehicle (EV) [8-9]. The NPC inverter has been most widely used for application in highpower high-voltage (or medium-voltage) drives nowadays, because the imposed voltage across each switching power devices is half fraction of the conventional two-level inverter with the same ratings of the device [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 interface with 20 kW 3-phase induction motors that proved to be suitable for HEVs. The references [5-11] propose 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 mediumvoltage 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, there is simplicity in extending the voltage to higher levels. In addition, diode clamped converters are widely used in medium and lowpower applications [12]. A Scott transformer topology is presented [13] to provide redundancy to the power switches in an Integrated Power Module (IPM) and a fault-tolerant scheme is simulated to test the operation of a permanent-magnet synchronous machine in a plug-in hybrid electric vehicle (PHEV).

In this paper, a NPC seven-level inverter is used to feed traction motor (PMSM). This multilevel inverter allow to get a best 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.

### 2. SYSTEM DESCRIPTION AND MODELING

The global system is detailed in Figure 1. It is composed of two sources, the first one is the FC and the second one is the UC that are connected to the DC link bus through a unidirectional DC/DC and 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 carried out using MATLAB/Simulink environment under various operating conditions to show the effectiveness of proposed methodology. Simulation results reflect the effectiveness of proposed scheme in steady state and dynamic operating conditions.



Figure 1. FC/UC hybrid electric vehicle topology

#### 2.1 PEMFC modeling

The polymer electrolyte membrane fuel cell (PEMFC) is the main energy source for the vehicle. Its cell voltage and its total power are defined by the following equations [14-15]:

$$V_{FC} = E_{nernst} + U_{act} - U_{ohm} - U_{con}$$
(1)

$$U_{ohm} = \frac{I_{FC}}{A} \left[ \frac{\frac{181.5[1+0.03(\frac{I_{FC}}{A})+0.6\frac{T}{303}(\frac{I_{FC}}{A})^{2.5}]}{[\lambda - 0.0633 - 3(\frac{I_{FC}}{A})]\exp[4.1(1-\frac{303}{T})]} I_{FC} + A R_c \right] (2)$$

$$U_{act} = -\left[\xi_1 + \xi_2 T + \xi_3 T \ln(C_{o2}) + \xi_4 T \ln(I_{FC})\right]$$
(3)

$$U_{cond} = -B_{FC} \ln \left( 1 - \frac{I_{FC}}{I_{FC,\text{max}}} \right)$$
(4)

The expression of the Nernst equation is given as [16]:

$$E_{Nernest} = 1.229 - 0.85 \times 10^{-3} (T - 298.15) + 4.3085 \times 10^{-5} T (\ln(P_{H2}) + 0.5 \ln(P_{e2}))$$
(5)

The parameters of the FC are given in Table 1.

### Table 1. Parameters of fuel cell

	Symbol	Values
Nominal power	P <sub>FC,nom</sub>	35 kW
Internal resistance	R <sub>FC</sub>	3 mΩ
Activation over voltage constant	В	0.0477 V
Hydrogen valve constant	K <sub>H2</sub>	4.22.105k.mol.atm/s
Temperature	Т	65°C

#### 2.2 UC system modeling

The UltraCapacitor (UC) is used as an auxiliary power source. It is dedicated for applications where both energy and power density are needed. Even if their energy density is ten times lower than the energy density of batteries, Ultracapacitors have a long life virtually unlimited cycle life, they offer low resistance thus enables high load currents, offer rapid charging without the danger of overcharging and they are safe to use. A circuit model topology is selected, as shown in Figure 2.



Figure 2. Equivalent circuit of ultracapacitor

It is composed of a capacitance  $C_{Cell}$ , a series resistance  $r_s$  corresponding to the charge and discharge resistance, a parallel resistance  $r_p$  consisting of the self-discharge losses.

The modeling of the UC units is detailed by the following equations [17]:

$$V_{Cell} = r_s i_{Cell} + \frac{1}{C_{Cell}} \int \left( i_{Cell} - \frac{V_{Cell}}{r_p} \right)$$
(6)

$$V_{UC} = \eta_{UC} V_{Cell} \tag{7}$$

The parameters of the UC are given in Table 2.

Table 2. parameters of ultracapacitor

	Symbol	Values
Capacity	F	500 F
Resistance	$R_{UC}$	2.4 mΩ
Voltage	$V_{UC}$	16.2 V
Maximal power	<b>P</b> UCmax	40 kW

# 2.3 PMSM modeling

Permanent-magnet synchronous machines are gradually considered the better choice of traction motors of HEV, due to their high power density and high efficiency. Modeling of a PMSM without damper winding has been developed using the following assumptions [18]: Saturation is neglected; the induced EMF is sinusoidal; Eddy currents and hysteresis losses are negligible; there are no field current dynamics. Voltage equations are given by [19-20]:

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d}{dt} \phi_{ds} - \omega \phi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d}{dt} \phi_{qs} - \omega \phi_{ds} \end{cases}$$
(8)

The mechanical equation of the synchronous machine can be written:

$$J_m \frac{d\Omega}{dt} = C_{em} - C_r - f\Omega$$
<sup>(9)</sup>

where, the electromagnetic torque can be expressed by:

$$C_{em} = \frac{3}{2} P \left( \phi_d i_q - \phi_q i_d \right) \tag{10}$$

Such as: 
$$\omega = P\Omega$$
 and  $\Omega = \frac{d}{dt}\theta$ 

Flow-current relations are given by:

$$\begin{cases} \Phi_{ds} = L_{ds} i_{ds} + \Phi_{f} \\ \Phi_{qs} = L_{qs} i_{qs} \end{cases}$$
(11)

#### 2.4 Seven-level NPC inverter modeling

A three-phase seven-level NPC inverter is shown in Figure 3.



Figure 3. Three-phase 7-level NPC inverter circuit topology

The DC bus consists of six capacitors,  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$ ,  $C_5$  and  $C_6$ . For DC-bus voltage  $V_{dc}$ , the voltage across each capacitor is  $V_{dc}/6$ , and each device voltage stress will be limited to one capacitor voltage level  $V_{dc}/6$  through clamping diodes.

To explain how the staircase voltage is synthesized, the

neutral point n is considered as the output phase voltage reference point [21]. There are seven switch combinations to synthesize seven level voltages across (a, b, c) and n is given in Table 3.

Table 3. Switching states for a seven level NPC inverter

V <sub>0</sub>	Vdc/2	V <sub>dc</sub> /3	V <sub>dc</sub> /6	0	Vdc/6	V <sub>dc</sub> /3	Vdc/2
<b>S</b> 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
<b>S</b> 4	1	1	1	1	0	0	0
<b>S</b> 5	1	1	1	1	1	0	0
<b>S</b> 6	1	1	1	1	1	1	0
<b>S</b> 7	0	1	1	1	1	1	1
$S_8$	0	0	1	1	1	1	1
<b>S</b> 9	0	0	0	1	1	1	1
S10	0	0	0	0	1	1	1
S11	0	0	0	0	0	1	1
S12	0	0	0	0	0	0	1

#### 2.5 Vehicle modeling

As shown in Figure 4, the vehicle is considered as a solid point moving subjected to forces along the longitudinal axis: 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  $F_{slope}$  [22-23].



Figure 4. Dynamics of the vehicle

$$F_{aero} = \frac{1}{2} \rho A C_x V_v^2 \tag{12}$$

$$F_{slope} = M_{v}g\sin(\delta) \tag{13}$$

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

$$M_{v}\frac{dv_{v}}{dt} = F_{t} - F_{roll} - F_{aero} - F_{slope}$$
(14)

The traction force of each wheel is given by the following expression:

$$\frac{F_{i}}{2} = \frac{T}{R_{\omega}} \tag{15}$$

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

Table 4. Vehicle parameters

Values
800 kg
.75 m <sup>2</sup>
0.009
$2 \text{ kg/m}^3$
.81 m/s <sup>2</sup>

### 3. CONTROL SYSTEMS AND REGULATION

The current regulation of DC/DC converters and bus voltage control using PI regulator are presented in this section. The energy management strategy using fuzzy logic is given. The traction motor is fed by seven level inverter to optimize the power required by a hybrid sources. The speed of vehicle is controlled using sliding mode control.

## 3.1 Speed regulation and inverter control of PMSM

PMSMs nowadays are commonly used in industrial applications in the field of motion control. Major reasons for their popularity are high power density and high efficiency [12]. But, PMSM is multivariable, non-linear, strongly coupled, and very sensitive to outside disturb and parameter variation, which makes it difficult for applied conventional linear control technologies to get perfect control performance of PMSM [24-25]. Rapidly developing robust control theory provides an ideal solution for this problem. Sliding Mode Control (SMC) is a special robust control method, which can self-adjust controller structure online and be non-sensitive to parameter variation and outside disturb. SMC is so fit for solving control problems of non-linear uncertain system [26].

The Figure 5 shows the vector control of the PMSM.



Figure 5. Vector 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:

$$U = U_{eq} + U_n \tag{16}$$

With: U - control variable  $U_{eq}$  - size equivalent command,

 $U_n$  - size discontinuous control.

$$U_n = K \ sign \ \left(S(x)\right) \tag{17}$$

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 [27-28]:

$$S(x)\dot{S}(x) \le 0 \tag{18}$$

The sliding surface is defined by:

$$S(\Omega) = \Omega_{ref} - \Omega \tag{19}$$

The derivative of this surface is given by the following expression:

$$\dot{S}(\Omega) = -C_1 \Omega + \frac{C_r}{J} + \Omega_{ref} - (C_2 I_{ds} + C_3) I_{qs} \qquad (20)$$

## 3.2 UC converter control and DC bus voltage regulation

#### 3.2.1 DC bus voltage control

The bidirectional buck-boost converter is a component key for the hybridization. It is an electrical device that transforms unregulated DC power to regulated DC bus power in the hybrid configuration. We should control PWM of  $T_{12}$  and  $T_{22}$ to make voltage of DC stable and limit the UC current. The control strategy of bidirectional converter is shown in Figure 6.



Figure 6. DC bus voltage regulation and the UC converter control

#### 3.2.2 FC converter control

Figure 7 shows a boost DC/DC converter with fuel cell current regulation. The FC power reference is divided by the FC voltage to obtain the reference value. The FC current is measured and compared with a reference value, and the error signal is processed through the PWM (pulse with modulation) controller, which is a simple proportional integral (PI) controller.



Figure 7. Fuel Cell converter control

## 4. ENERGY MANAGEMENT USING FUZZY LOGIC

In recent years, many studies have adopted intelligent techniques to perform energy management in hybrid systems. Principally, fuzzy logic as required for many applications [29]. Fuzzy systems are control methods that can be effectively and powerfully used for nonlinear systems in which deriving a mathematical model that represents the system operation is difficult [30-31]. The energy management strategy using fuzzy logic (Figure 8) coordinates all the elements in the system to provide continuously the necessary traction, to keep constant the DC bus voltage ( $V_{bus}$ ) and maintain the UC SOC (state-of-charge).



Figure 8. 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 FLC is the fuel cell power ( $P_{FC}$ ).

#### 5. SIMULATION RESULTS AND INTERPRETATION

To validate the proposed work, simulation studies have been curried by using MATLAB/SIMULINK. The results have been done using an aleatory drive cycle of 200 seconds and with 120 km/h maximum speed as shown in Figure 9.



Figure 9. Speed vehicle during the proposed cycle





Figure 10. Traction motor power and electromagnetic torque



Figure 11. Fuel cell voltage, fuel cell current and fuel cell power



Figure 12. Fuel cell efficiency [%]

**Table 5.** Comparison of voltage THD and current THD between the two inverter configurations

Inventor configuration	<b>THD (%)</b>		
Inverter comiguration	Voltage	current	
Two-level inverter	69.87 %	30.25 %	
Seven-level inverter	20.09 %	16.7 %	

The speed of the vehicle follows the reference speed as shown in Figure 9, but with the use of a multilevel inverter, the speed is smoother compared to that obtained with the twolevel inverter.

Figure 10 shows the power and the electromagnetic torque of PMSM. It seen that the electrical and mechanical performance of traction motor are significantly improved using 7-level inverter. Current and voltage THD (Table 5) are greatly decreased with the multilevel inverter.

The electric parameters of fuel cell are shown in Figure 11, 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 Figure 12, is better.

# 6. CONCLUSION

Our main objective in this work was the improvement of the fuel cell performance. Since the characteristics of the fuel cell depend heavily on the load, multilevel inverter was the right solution to enhance the electrical and mechanical performance of the traction motor.

The different simulation results obtained, showed the interest of using a 7-level inverter in HEVs by enhancing the performance of the load, increasing 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 get a better quality of the power of the ultracapacitor and also 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, ensures continuity of service in the event of semiconductor failure and increase the lifetime of the vehicle.

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# NOMENCLATURE

V <sub>FC</sub>	FC cell output voltage, V
Enernest	FC cell potential open-circuit voltage, V
Uact	Activation voltage drop, V
$U_{ohm}$	Ohmic voltage drop, V
Ucond	Concentration voltage drop, V
I <sub>FC</sub>	Fuel cell current density, A.cm <sup>2</sup>
А	Cell active area, cm <sup>2</sup>

R <sub>c</sub>	Equivalent resistance to proton conduction,
T	$\Omega$
ן ר	Operation temperature, <sup>1</sup> C
ςi	parameters corresponding to $U_{act}$ ,
$B_{FC}$	Empiric coefficient for the concentration
Pup	Partial pressure of hydrogen atm
P <sub>02</sub>	Partial pressure of oxygen atm
V <sub>G</sub> u	LIC cell voltage V
v Cell	UC series resistance O
r	UC parallel resistance. O
	UC cell capacitance, E
CCell	UC cells number put in corrise
II <sub>uc</sub>	UC cens number put in series
V <sub>UC</sub>	UC voltage, V
$\Phi_{qs}$	Quadrature flux axis, Wb
Ω	Mechanical speed of the rotor, rpm
ω	Electrical speed of the rotor, rd/s
$J_m$	Moment of the inertia, $kg \cdot m^2$
Cem	Electromagnetic torque of PMSM, N.m
Cr	Resistance torque, N.m
f	Viscous friction coefficient, N·m·s
Р	Number of pole pairs
L <sub>ds</sub>	Direct stator inductance, H
$L_{qs}$	Quadrature stator inductance, H
$\Phi_{ m f}$	Flux induced by magnet, Wb
F.	Traction force caused by the action of the
<b>-</b> (	two drive wheels, N
Froll	Friction force to advancement, N
$F_{aero}$	Effort of aerodynamic resistance, N
$F_{slope}$	Resistance force of mounted side, N
$M_{ m v}$	The vehicle weight, kg
g	The gravitational acceleration, 9,81 m/s <sup>2</sup>
$f_r$	The resistance coefficient of the tire rolling
ρ	The air density, $N \cdot m \cdot s/rd$
$A_v$	Front area of the vehicle, m <sup>2</sup>
C <sub>x</sub>	Aerodynamic drag coefficient
$V_v$	The vehicle speed, m/s
$T_r$	The electromagnetic torque, N·m
$R_w$	The wheel radius, m