Active Filtering and Power Factor Correction for Electric Vehicles

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***Abstract*-- This paper discusses the performance of an active power filter plug in the Powertrain of the electric vehicle. The object of this filter is to mitigate harmonic currents produced by the non linear loads and to ameliorate the power factor of the source. For such application, regarding the fact that the load dynamically changes according to the variation of the system frequency (50Hz to 300Hz) which depend on the alternator speed (1000rpm to 6000rpm), an enhanced filtering system is required. The proposed filter is a cascaded multilevel inverter controlled by phase disposition carriers pulse width modulation (*PDPWM*) technique. The performance of this filtering system is checked through a simulation in the Matlab/Simulink platform.**

***Index Terms*—electric vehicle, active power filter, cascaded multilevel inverter, identification strategy, modulation technique.**

1. Nomenclature

V_s, V_r: stator and rotor voltages
i_s, i_r: stator and rotor currents
ϕ_s, ϕ_r: stator and rotor flux
R_s, R_r: stator and rotor resistances per phase
L_s, L_r: stator and rotor inductances per phase
M_{sr}: mutual inductance
PCC: point of common coupling
ISC: maximum short circuit current at *PCC*
IL: maximum demand load current (fundamental frequency component) at the *PCC*
THD: Total Harmonic Distortion
TDD: Total distortion demand
PWM: Pulse Width Modulation

2. Introduction

In the recent years, scientific searches seek to improve the efficiency of electric vehicles thanks to their ability to reduce vehicular emissions and ecological pollutions and simultaneously to increase fuel efficiency of the vehicle. This type of vehicles is also characterized by the simple design of the Powertrain compared the other kinds of vehicles [1]. Despite the variety in electric vehicle configurations (battery electric vehicle BEV, hybrid electric vehicle HEV, plug in hybrid electric vehicle PHEV), the drive train consists of 3 main parts which are the energy sources (rechargeable batteries, fuel cells and ultra capacitors), the traction motor and finally the power converters to adjust the voltage depending to the load need. But owing to the proliferation of the use of the power electronics and especially the AC/DC converter into the electric vehicle structure, many power quality problems (harmonics, reactive power…) appear and affect the performance of the system and that of the traction motor. Among the harmful effects of harmonics in the motor, there are noise vibration, low efficiency, excessive losses, overheating and shorten motor life operation [2]. Thus, to avoid these undesirable consequences, the table 1 presents the limits of harmonic current emissions which must not be exceeded according to the electromagnetic compatibility EMC Standard **IEEE-519** [11].

TABLE I

IEEE 519 Current Distortion Limits

Harmonic Current Limits for Non-Linear Load at the Point-Of-Common-Coupling with Other Loads, for Voltages 120-96.000 Volts						
Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order						
TDD	35<50	23<35	17<23	11<17	<11	ISC/IL
5	0.3	0.6	1.5	2	4	<20
8	0.5	1	2.5	3.5	7	20<50
12	0.7	1.5	4	4.5	10	50<100
15	1	2	5	5.5	12	100<1000

In order to respect these limits and to aiming more stability and better design of the alternator, the adding of a harmonic filter into the electric vehicle powertrain is requisite. Among the existing solutions of filtering, the shunt active power filter is chosen as one of the powerful tools for the mitigation of harmonic currents and the compensation of the power reactive and of the unbalance of non linear loads. Then, this paper presents the design of a shunt active power filter which is implemented into the vehicle Powertrain as shown in fig.1.

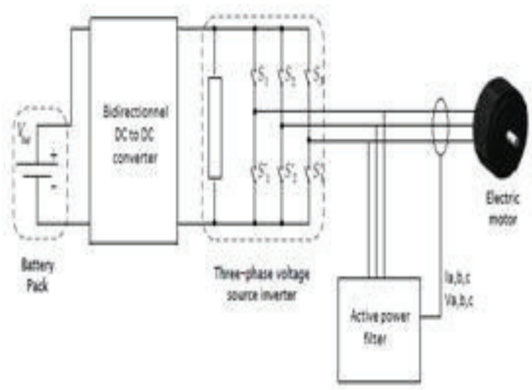


Fig. 1. the filter location into hybrid vehicle Powertrain

In the literature, there is research on severing issues related to the design and the control of the shunt active power filter such as the choice of the filter topology and the selection of identification strategy and modulation technique. On the other hand, for vehicle application, the variation of the supply frequency according to the motor speed brings new challenge essentially in the filter control.

In this paper, we start with the description of the alternator model. Then, we present the filter topology selected for this application. In the fourth section, we focus on the choice of the control technique which allows the better mitigation of harmonics and the correction of the power factor considering the frequency variation. Finally, the efficiency of simulated system is checked with presenting the simulation results.

3. The alternator model

The traction motor is a synchronous alternator with salient poles. It can be presented by the following dynamic model:

$$V_s = R_s i_s + \frac{d\phi_s}{dt} \tag{1}$$

$$V_r = R_r i_r + \frac{d\phi_r}{dt} \tag{2}$$

Neglecting the iron losses of the rotor, the equations of the rotor and the stator voltages are depicted in the (d, q) frame by the following expressions:

$$V_{sd} = R_s i_{sd} - \omega_{dq}\phi_{sq} + \frac{d\phi_{sd}}{dt} \tag{3}$$

$$V_{sq} = R_s i_{sq} - \omega_{dq}\phi_{sd} + \frac{d\phi_{sq}}{dt} \tag{4}$$

$$V_{rd} = R_r i_{rd} + \frac{d\phi_{rd}}{dt} \tag{5}$$

With

$$\phi_{sd} = L_{sd} i_{sd} + M_{sr} i_{rd} \tag{6}$$

$$\phi_{sq} = L_{sq} i_{sq} \tag{7}$$

$$\phi_{rd} = L_{rd} i_{rd} + M_{sr} i_{sd} \tag{8}$$

$$\phi_{rq} = 0 \tag{9}$$

4. The active power filter topology

A. The selection of the harmonic filter topology

The design of the active power filter is studied deeply in the literature. Among the current filter topologies, the multilevel inverter takes more importance in research for the high and the medium power applications. But due to its ability to improve the waveforms and to optimize costs, its usefulness in the low power application increases. The most important features of multilevel inverter are the ability to:

- synthesize an output voltage with high quality and low distortion,
- operate with a lower switching frequency thereby minimizing switching losses,
- generate a smaller common mode voltage and reduce the stress in the motor bearing.

The most known topologies of multilevel inverter are the diode clamped inverter, the flying capacitor inverter and finally the cascaded inverter. This paper present an active power filter based on cascaded multilevel inverter. The choice of the cascaded topology is justified by the following advantages compared to the other multilevel inverter topologies [3]:

- the Lower cost for construction and maintenance,
- the ability to achieve the same number of the output voltage levels with the use of the smallest number of components,
- the non requirement of the extra components like the extra clamping diode and the voltage balancing capacitor in contrast to the other topologies,
- the decreasing of the potential shocks with the use of separate DC sources.

B. The cascaded inverter model

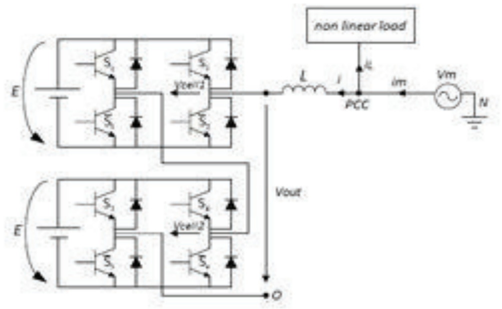


Fig. 2. Single phase multilevel inverter connected to the point common coupling

Fig.2 shows a phase of the cascaded inverter connected between the motor and the non linear load through a smoothing inductance *L*.

Each phase of the inverter consists of two cells connected in series. The output phase voltage is synthesized by the summation of the voltage produced by the different cells. For each bridge inverter, the sequentially connection between the voltage source and the ac side via the four power switches allows the generation of three voltages at the output: *-E*, 0, *E*. Thus, the phase ac voltage balances from *-2E*, *2E* with five levels. This is made the staircase waveform of voltage more closely to sinusoidal yet without filtering. The system parameters are given in the below Table2 where the switching function are defined by the continuous control signals δ_1 and δ_2.

TABLE II

System Parameters and Variables

Symbol	DESCRIPTION
L	Filter inductance
E	H-Bridge source voltage
$V_{cell1,2}$	H-Bridge output voltage
V_{out}	Cascaded inverter output voltage
V_m	motor voltage
i_m	motor current
i_l	Load current
i	Cascaded inverter current
δ_1, δ_2	Control signals

The equations that depict the cascaded H-bridge model as well known are given by [6]:

$$V_{cell1} = (S_1 + S_2 - 1)E = \delta_1 E \quad (10)$$

$$V_{cell2} = (S_3 + S_4 - 1)E = \delta_2 E \quad (11)$$

With $\delta_1, \delta_2 \in [-1,1]$

$$V_{out} = V_{cell1} + V_{cell2} \quad (12)$$

$$V_m = V_{out} + V_{ON} + L\frac{di}{dt} \quad (13)$$

With V_{ON} the tension between the source neutral and the point common of cascaded multilevel inverter.

$$V_{ON} = -\frac{1}{3}(V_{out1} + V_{out2} + V_{out3}) \quad (14)$$

Thus, the expression of the current motor is as follows:

$$\frac{di_m}{dt} = \frac{1}{L}(V_m - V_{out} + L\frac{di_l}{dt}) \quad (15)$$

Based to these equations, the control system will be determined in the next section.

5. CONTROL SYSTEM

The control system is composed by two essential blocks which are: the identification block and the regulation and control block.

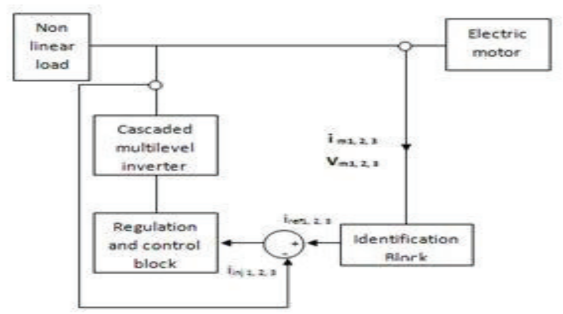


Fig. 3. The principle of the control system

The principle of the control system is shown in Fig.3. The identification algorithm extracted the motor current and voltage to calculate the harmonic current. Then, the regulation and control block generate the control signals to draw the same harmonic current at the output of cascaded inverter. Thus, the motor current keeps a sinusoidal waveform that is equal to the fundamental of the load current.

A. The identification block

This block permits a fast current decomposition based to identification algorithm to calculate the reference currents which must be injected in the PCC to eliminate the harmonic currents in the system.

There is a large number of current extraction methods in the time and frequency domains. In this paper, the compensation signals are determined with the using of the synchronous reference frame theory developed for the shunt active power filter. This theory is based on time domain reference signal estimation technique. Among its characteristics, there is this efficiency in steady state or transient as well as for generic current and voltage waveforms, the simplicity of the calculation, and the ability to control the filter in real time system. For this theory, the calculation of reference currents is consists of 5 steps which are described as below [10].

1. The transformation of the three phase load currents in the *αβ0* frame.
2. The transformation of the new frame currents to i_d and *iq* on the *d-q* rotary reference frame after the cancellation of their zero sequence components. The fundamental angular frequency ω is used as the synchronous angular frequency by the phase lock loop block (PLL).
3. In the new frame the fundamental components of motor current are transformed to dc components and the harmonic components become ac components with a frequency shift equal to the fundamental frequency as described in the following expression:

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{pmatrix} \qquad (16)$$

The use of a low pass filter is necessary to draw the harmonic components out of the current on d-q axis.

4. The transformation of the extracted harmonic current on *d-q* frame to (*α, β*) frame.
5. The calculation of the reference currents with the using of the zero sequence components calculated in the first step.

B. The control and regulation block

In order to generate the switching pattern of the multilevel inverter, we proposed the triangular carrier current controller method [5]. This type of current control based on the inverter features is characterized by a fast current controllability and a switching operation which allows the mitigation of the harmonics. This method consists of the extraction of the reference signal from the current error (the calculated reference current compared with the actual injected current) by means of the PI regulator. The regulator gains are calculated in order that the injected current follows the reference current for the different system frequencies as shown in Fig.4.

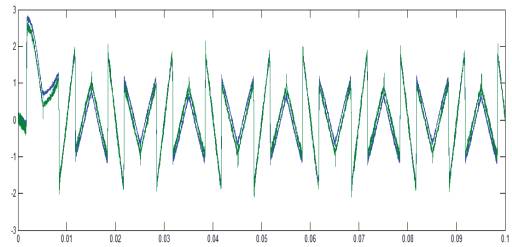


Fig. 4. The injected and the reference currents of filter for the frequency 50 Hz

For the modulation strategy, we choose the multi carrier based modulation sinusoidal PWM strategy owing to its simplicity and rapidity. Thus, the output signal of the PI regulator is compared with triangular carrier signals to generate the control signals. This method of control for the cascaded inverter has been deeply investigated in the literature describing its various carriers based disposition (PSPWM, PDPWM, PODPWM and APODPWM…) [7].

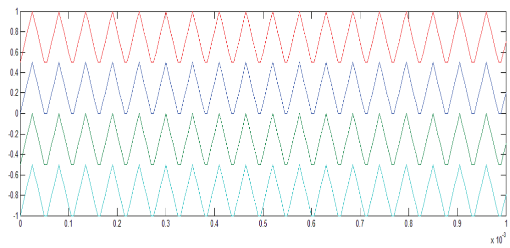


Fig. 5. PDPWM technique

Fig. 5 presents the phase disposition PWM (PDPWM) technique used in this paper. For each phase, the reference signal was compared to four triangular carriers which have the same frequency and amplitude and are in phase.

6. Simulation Results and Analysis

The performance of the proposed active power filter for the different frequencies of the system is checked through Matlab/Simulink platform. The correction of the power factor is verified by the implementation of a power factor calculator.

The expression of the power factor P_f is given by:

$$P_f = \cos(\varphi_1)\frac{1}{\sqrt{(1+THD^2{}_I)}} \qquad (17)$$

With

φ_1: The phase angle between the voltage and the fundamental component of the current.

THD_I: The total harmonic distortion of current

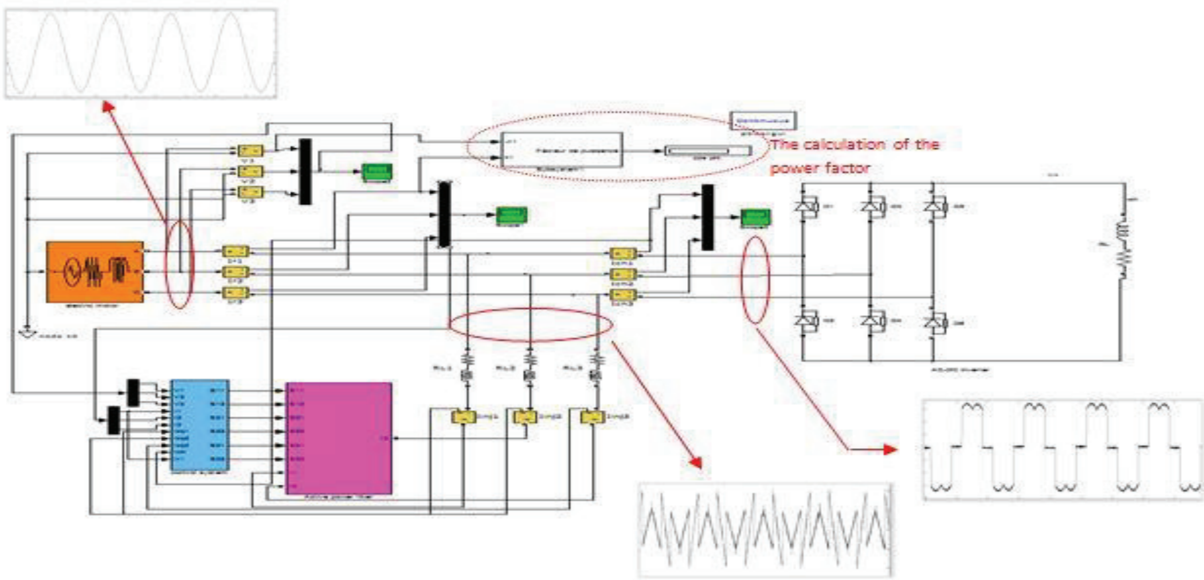
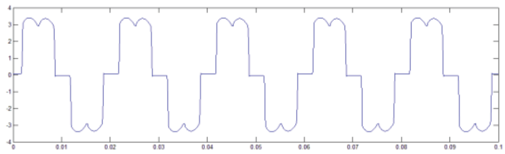


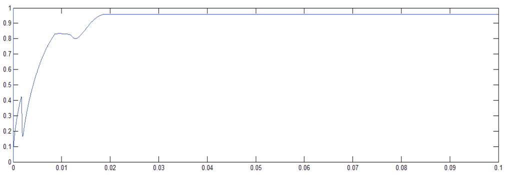
Fig. 6. The simulation model of the active power filter in Matlab/Simulink platform

The simulation model via MATLAB/SIMULINK is depicted in Fig.6.

Before filtering, the motor current keeps the same waveform of the load current with a power factor equal to 0.95 as shown in Fig. 7.



(a). The waveform of the current motor before filtering



(b). The evaluation of the power factor

Fig. 7. The current waveforms and the calculation of the power factor

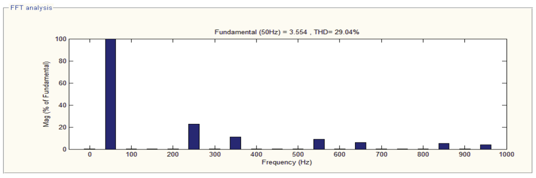
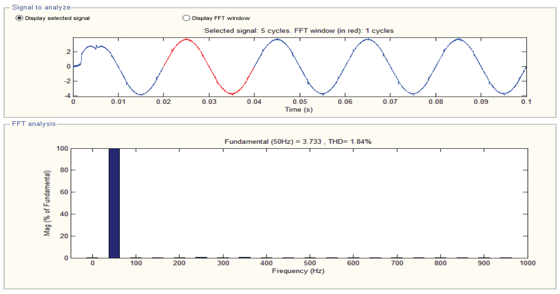


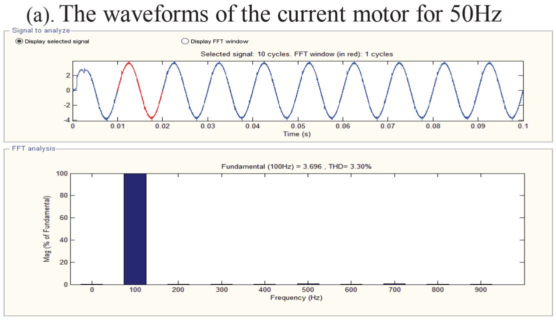
Fig. 8. The harmonic spectrum for the current motor before filtering

Fig.8 shows the harmonic spectrum of the first 20 harmonics. Without the active filter, the harmonics (5th, 7th, 9th, 11th, 17th, and 19th) are predominantly present, and the THD value of the motor current is 29.04% which is well beyond the limits of the current distortion set by IEEE 519.

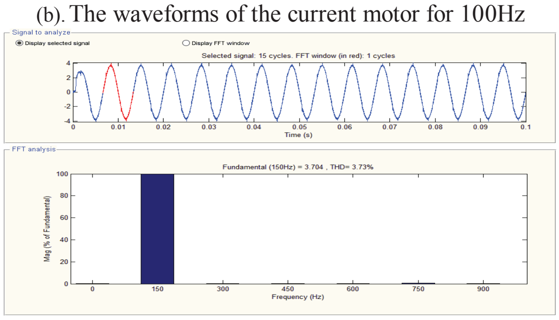
After filtering, by varying the frequency, the waveform and the harmonic spectrum of motor current are shown in Fig.9.



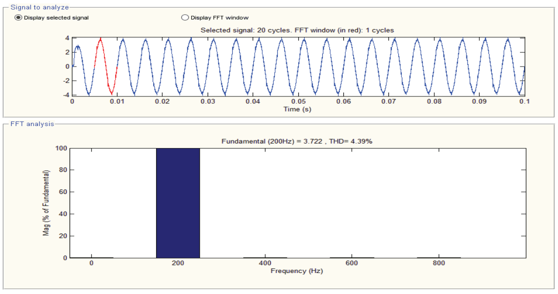
(a). The waveforms of the current motor for 50Hz



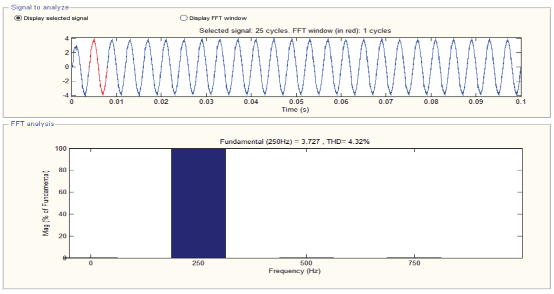
(b). The waveforms of the current motor for 100Hz



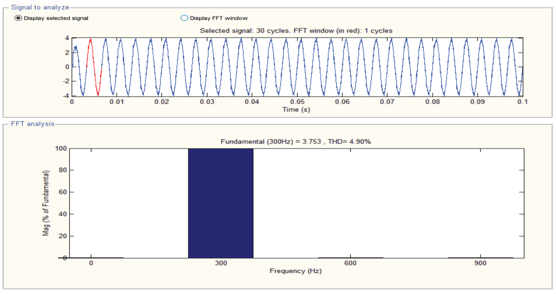
(c). The waveforms of the current motor for 150Hz



(d). The waveforms of the current motor for 200Hz



(e). The waveforms of the current motor for 250Hz



(f). The waveforms of the current motor for 300Hz

Fig. 9. The current waveforms and the harmonic spectrum for different frequencies

For the different values of frequency, the motor current keeps sinusoidal waveforms.

The limits of the current distortion are respected for the different frequencies (from 50Hz to 300 Hz) with a THD value less than 5%.In addition, the power factor keeps a constant value equal to 0.99 as shown in Fig.10.

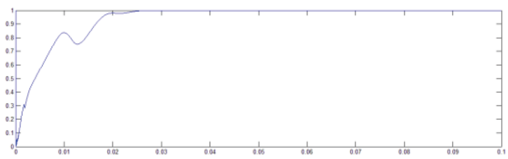


Fig. 10. The power factor evaluation for the different values of frequency

7. Conclusion

In this paper, the efficiency of the cascaded H-Bridge converter was discussed with Matlab simulation based on the synchronous reference frame theory for the identification strategy and the PWM technique. By comparing the simulation results before and after filtering for the different frequencies of system (from 50 Hz to 300 Hz), we notice that the THD value and the power factor has been improved and the harmonic currents have been reduced. Before filtering, the THD value was 29.04% and the power factor was 0.95. After filtering, the system retains a constant power factor for 0.99. Also, the THD value has become smaller and does not exceed the limits set as shown in the below table.3.

TABLE III

The Simulation Results

Frequency (Hz)	THD VALUE (%)
50	1.84
100	3.30
150	3.73
200	4.39
250	4.32
300	4.90

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