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A Case Study on the Conversion of an Internal Combustion Engine Vehicle into an Electric Vehicle

Delfim Pedrosa, Vítor Monteiro, Henrique Gonçalves, Júlio S. Martins, João L. Afonso
ALGORITMI Research Centre – University of Minho
Guimarães, Portugal
{delfim.pedrosa | vitor.monteiro | henrique.goncalves | julio.martins | joao.l.afonso}@algoritmi.uminho.pt

***Abstract*—This paper presents the conversion process of a traditional Internal Combustion Engine vehicle into an Electric Vehicle. The main constitutive elements of the Electric Vehicle are presented. The developed powertrain uses a three-phase inverter with Field Oriented Control and space vector modulation. The developed on-board batteries charging system can operate in Grid-to-Vehicle and Vehicle-to-Grid modes. The implemented prototypes were tested, and experimental results are presented. The assembly of these prototypes in the vehicle was made in accordance with the Portuguese legislation about vehicles conversion, and the main adopted solutions are presented.**

***Keywords*—Electric Vehicle; Conversion; Powertrain; Batteries Charging; AFIR-S Motor.**

I. INTRODUCTION

Oil prices are growing every day, which results from the general idea that oil is a resource that will be virtually exhausted in the next 50 years. Whereas, it is expected an increase of the overall vehicles number from 700 million to 2.5 billion during the same period [1], [2]. Alternative solutions are needed, and are being proposed. Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) that main manufactures are proposing, reveals a change in cities mobility paradigm. Furthermore, several organizations and energy experts are suggesting new policies to encourage research, development, and demonstration projects promoting EVs.

When the subject is EVs research, generality, is made an association with new and revolutionary vehicles. However, low cost solutions using reliable off-the-shelf components can also be proposed [3]. This way, the conversion of Internal Combustion Engine (ICE) vehicles in EVs is an attractive solution for the transitory period of coexistence. This process is called “electric vehicle conversion” [4]-[6].

In terms of engineering, this is a challenging process that needs knowledge about mechanics and electronics. The main systems that need to be integrated are the electric motor and respective controller, an energy storage system and corresponding charging system. Different solutions for the energy storage system are being proposed, however, the most common are batteries [2], [7]-[9]. Therefore, a batteries charging system is also needed.

Traditionally, batteries charging systems are implemented with static power converters. Different topologies can be used [10]. In order to respect batteries technology, different charging algorithms need to be used. Batteries charging systems can also be used to transform EVs and HEVs in an energy storage system, which receives and delivers energy, contributing to the power grid stability. Thus, besides charging batteries (Grid-to-Vehicle, G2V), the energy can also flow in opposite sense (Vehicle-to-Grid, V2G) [11], in accordance with power grid characteristics and the driver benefits.

This paper addresses the conversion of an ICE into an EV, labelled as CEPIUM (Carro Elétrico Plug-In da Universidade do Minho). The design, and prototype implementation, of all the necessary elements is presented, namely, the powertrain power electronics converter and batteries charging system with G2V and V2G features.

II. EV CONSTITUTIVE ELEMENTS

In a conversion process the characteristic of the EVs can be defined by the owner of the vehicle, in accordance with his needs. This specification will define the choice of the technical solutions that best suits. The conversion presented in this paper had three main initial objectives. The first one was to have a vehicle that could be in accordance with the Portuguese legislation. This is very important in order to facilitate authorities’ ratification. The second objective was to have 60 km of autonomy, to enable a round-trip between the University’s Campus (Guimarães and Braga). The last objective, but probably the most important one, was to only integrate new technologies whose design and implementation was developed inside the research group.

A. Electric Motor

Several types of electric motor can be used in conversions. All the existing technologies have advantages and disadvantages. Its selection should be made in accordance with the required performances for the vehicle. Axial flux permanent magnet synchronous motors are the most used nowadays due to technological advantages [12], [13], namely:

- High efficiency;
- High power density;
- Reduced engine size for the same power;
- Low maintenance costs;
- High power factor;
- Constant speed.

The Portuguese legislation imposes the mounting of the electric motor without removing or weakening any structural elements of the vehicle. Also, imposes that the electric motor´s power be less than the power of the original ICE. Considering this limitations and the initial specifications for the CEPIUM conversion was selected the AFIR-S (Axial Flux Slotted

Internal Rotor External Stator Permanent Magnet) motor shown in Fig. 1, whose main characteristics are presented in Table I.

B. Energy Storage System

The energy storage system is one of the main critical elements in EVs and HEVs. It defines the vehicle autonomy and represents an important portion of the vehicle weight. According to the storage methods different systems can be used. From such systems, batteries are the most popular, mainly due to its cost, energy density and technology maturity.

Different batteries technologies can be found in the market. However some are more adequate for powertrain applications than others [14]. The choice of one technology also depends on the vehicle specifications. So, for the CEPIUM conversion were chosen Absorbed Glass Matt (AGM) batteries, due to its reduced weight, increased energy density, improved reliability, and lower cost. Typically, AGM batteries have very low internal resistance, and are capable to deliver high currents on demand, offering a relatively long lifespan, even with large Depth-of-Discharge (DoD). The chosen batteries have a 50% of DoD for 1100 cycles, and are 100% recyclable [15]. Considering the required autonomy it was designed a 6.7 kWh battery pack.

C. Developed AFIR-S Motor Controller

Several manufactures have commercial solution to drive electric motors, many of them dedicated to EVs powertrains. However, as aforementioned, one of the main CEPIUM conversion objectives was to only integrate technologies whose design and implementation was developed inside the research group. Therefore, the controller shown in Fig. 2 was designed and developed.

Fig. 1 AFIR-S motor used in the conversion.

TABLE I. MOTOR'S CHARACTERISTICS

Characteristics	**Value**	**Unit**
Nominal Power P_n	30	kW
Speed ω	6000	rpm
Nominal Voltage V_n	187	V
Nominal Current I_n	113.5	A
Torque T	47.7	Nm
Number of Poles p	8	-
Nominal Frequency f	400	Hz
Stator Resistance R_s	19.35	mΩ
Inertia J	5.86	mkgm^2
d-axis Stator Inductance L_d	100	µH
q-axis Stator Inductance L_q	160	µH
Voltage constant k_e	42.1	V/1,000 rpm

This controller includes a three phase inverter, a digital control system, one monitoring panel, and some data acquisitions and protection systems. The power converter is composed by three IGBTs modules (IGBTs legs), drive circuits and snubber capacitors. The digital control system was implemented in a 32-bit floating-point Digital Signal Controller (DSC) TMS320F28335. The monitoring panel is composed by a 20X4 display and selection buttons. The signal conditioning and command boards are used to adapt the electric signals between the control system and the three phase inverter (sensors and command signals).

D. Developed Batteries Charging System

More than just charging EVs batteries, the charging systems major role is the contribution to a new perspective about the EVs integration in the power grid. Due to V2G operation, EVs are not seen as a problem anymore but as a power grid asset. Therefore, for the CEPIUM conversion was developed a batteries charging system with G2V and V2G features. Also grid power quality issues were respected, namely, sinusoidal current and unitary power factor [16].

Fig. 3 shows the batteries charging system prototype that was developed for CEPIUM. This charging system is composed by an ac-dc bidirectional converter and a dc-dc bidirectional converter. The ac-dc converter uses a full-bridge full controlled topology using four discrete IGBTs. In the dc-dc converter are used two IGBTs. The bidirectional power flow is obtained through an adequate control of the IGBTs.

III. POWERTRAIN CONTROL SYSTEM

In literature are discussed many control theories for the AFIR-S motors. Considering the specific characteristics of an EV powertrain system the Field Oriented Control (FOC) has revealed as the most adequate for such conversion. This control has as main advantage the independence of the stator flux control from the motor torque. When the motor is represented in a two axes orthogonal *d*-*q* coordinates system the direct

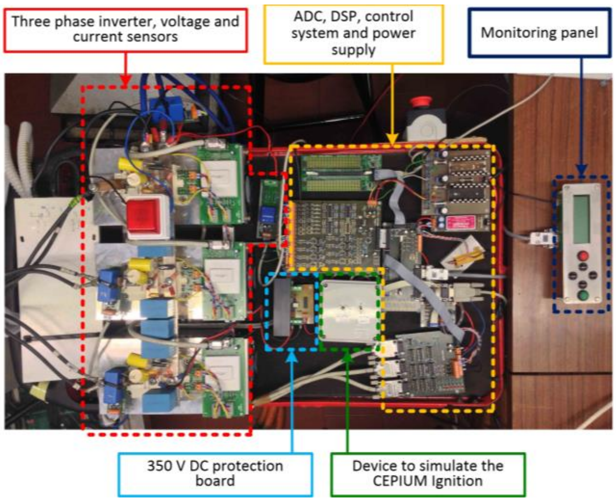

Fig. 2 Developed AFIR-S motor controller.

Fig. 3 Developed batteries charging system.

component represents the stator flux, and the quadrature component represents torque [17]-[19].

In order to translate the reference voltage, produced by the FOC, in gate pulses for the inverter semiconductors different pulsewidth modulation techniques can be used [20]. Knowing that the reference voltage is a vector, and considering the high performance of the space vector modulation technique, it was the natural choice.

With the goal of validating the implemented FOC the motor behavior was assessed using a test bench [21] set to apply a mechanical load of 40 Nm. In Fig. 4 are shown the motor's voltages and currents. The RMS value of the voltages and currents were of 66.3 V and 101.7 A, respectively.

In Fig. 5 are presented the waveforms of the reference I_{qref} and the motor current I_q during the test. Four different time instants are depicted. At instant t_1 the reference I_{qref} is changed from 0 to 200 A. The I_q follows the reference up to instant t_2, when it starts to decrease up to 119 A. This occurs because the motor finishes accelerating and it only needs to produce the mechanical load torque. At t_3 the reference I_{qref} is set to zero, and the current I_q follows the reference, but with a slight oscillation around zero up to instant t_4, when the motor stops running.

IV. BATTERIES CHARGING SYSTEM

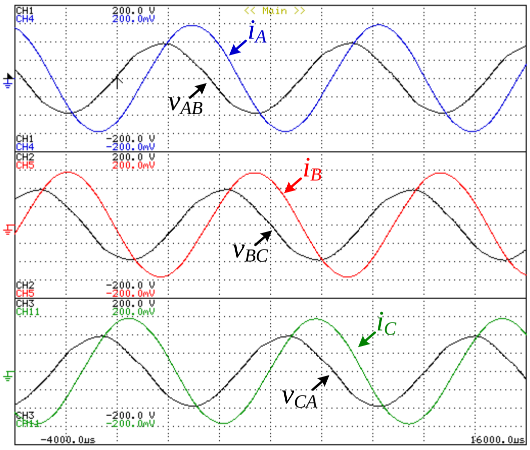

Fig. 4 Voltages (50 V/div) and currents (50 A/div) in the motor.

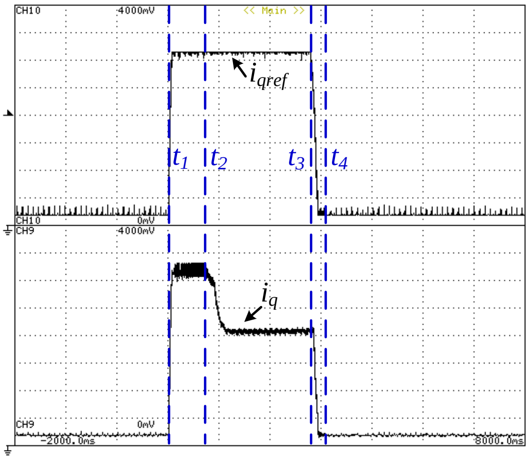

Fig. 5 Stator *d*-*q* axis current reference I_{qref} and I_q (90 A/div) current in the motor.

The batteries charging system control algorithm should be defined taking into account batteries nominal values and chemical technology. Also different voltage or current charging stages should be implemented in accordance with manufacturers' specifications.

In Fig. 6 are presented the power grid voltage and current waveforms during the Grid-to-Vehicle (G2V) charging process. It can be seen that the current is sinusoidal and is in phase with the power grid voltage, contributing to preserve the grid power quality. In Fig. 7 are also shown the power grid voltage and current waveforms, but during the Vehicle-to-Grid (V2G) discharging process, when part of the energy stored in the batteries is delivered back to the power grid. In both cases the batteries state of charge is monitored, and the batteries nominal values are respected aiming to preserve their lifespan.

V. ASSEMBLY OF THE ELECTRIC VEHICLE

The Portuguese legislation about vehicles conversion defines that the total weight of the vehicle after the conversion should not be higher than the gross weight defined by its manufacturer. The Volkswagen Polo has a good relation between its tare and gross weight, this characteristic was the main reason why it was chosen for the CEPIUM conversion.

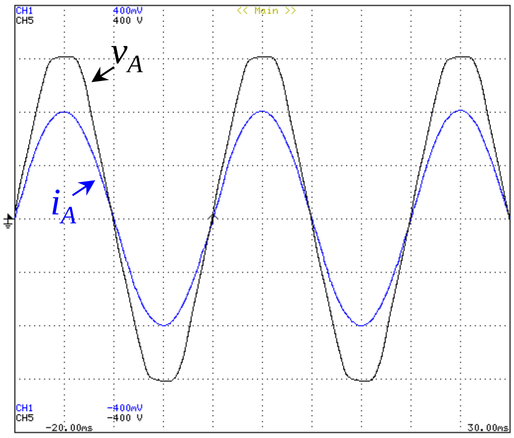

Fig. 6 Power grid voltage (100 V/div) and consumed current (2.5 A/div) during the Grid-to-Vehicle (G2V) charging process of the batteries.

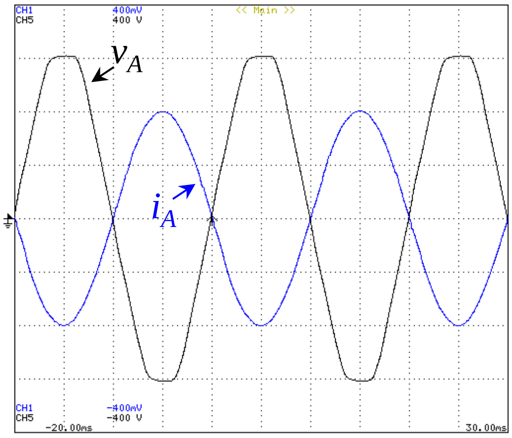

Fig. 7 Power grid voltage (100 V/div) and consumed current (2.5 A/div) when part of the energy stored in the batteries is delivered back to the power grid (operation in Vehicle-to-Grid mode - V2G).

Fig. 8 Final look of the CEPIUM after the conversion.

(a) **(b)**

Fig. 9 System assembly: (a) Power electronics; (b) Electric motor and gearbox.

Also, the absence of assisted steering has influenced the choice, since the replacement of the conversion of the assisted steering is avoided, reducing the conversion complexity.

In Fig. 8 is presented the final look of the CEPIUM after the conversion. Fig. 9 (a) shows the assembly of the power electronics in the front part of the vehicle. Fig. 9 (b) shows the assembly of the motor to the original gearbox. This configuration was chosen to reduce the complexity of the mechanical modifications. Therefore, the ICE can be directly replaced by the electric motor reducing the mechanical adaptations and system complexity.

(a) **(b)**

Fig. 10 Batteries: (a) Assembly under the Electric Vehicle; (b) Electrical conections.

In order to ensure that the maximum axes weight, defined by the vehicle manufacturer, was not exceeded the batteries were distributed by two areas of the vehicle. A smaller group was placed in the front of the vehicle, using the free space left by the removal of the ICE. The main group was placed in the free space originally occupied by the gasoline tank (Fig. 10).

VI. CONCLUSIONS

This paper presented the conversion of a traditional Internal Combustion Engine vehicle into an Electric Vehicle. The main constitutive elements that were integrated were presented. Both the powertrain and batteries charging power converters were developed for this conversion. The powertrain is composed by a three-phase inverter with Field Oriented Control and space vector modulation. The developed batteries charging system has Grid-to-Vehicle and Vehicle-to-Grid features. Also grid power quality issues were respected, such that it operates with sinusoidal current and unitary power factor.

The assembly of the main components of the Electric Vehicle was presented, wherein the Portuguese legislation about vehicles conversion was respected.

Currently, the converted Electric Vehicle, named CEPIUM, is being submitted to field tests in order to validate and improve the developed systems. Moreover, regenerative braking features are under development.

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