

Conversion of an Internal Combustion Engine Vehicle into an Electric Vehicle

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Abstract — In this paper is described the conversion of an Internal Combustion Engine (ICE) vehicle into an Electric Vehicle (EV). The main steps of this conversion are briefly described, especially the standards to legalize EVs in Portugal, and the EV elements, mainly, the electric motor and its respective controller, and the batteries with the charging system. This paper also presents the modifications performed in the vehicle that was transform it in an EV, and that are specific of the vehicle used, mainly the adaptations to assemble the electric motor in the vehicle, and the disposition of the batteries' bank on the vehicle.

Keywords – *Electric Vehicle; ICE to EV Conversion, Electric Motor; Batteries; Axial Flux Permanent Magnet Motor, AFIR-S Motor.*

I. INTRODUCTION

The recent escalades in the oil price and the CO₂ restrictions will change the actual paradigm in the transportation sector, aiming the electric mobility, mainly through Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs). Thus, several organizations and energy experts suggest policies to encourage research and demonstration projects of these vehicles

When the subject is EVs, almost always is made an association to new and revolutionary vehicles, however as alternative to a new EV, there is the possibility to build an EV with ease, low cost, and reliable, off-the-shelf EV components [1]. For this goal, the Internal Combustion Engine (ICE) in an existing combustion-powered vehicle is replaced by an electric drive train. This process, denominated as "Electric Vehicle Conversion", is an engineering challenge that needs mechanical and electronic knowledge and has become popular in the last years, among hobbyists and schools, but it is expected a growth in the commercial potential in the near future.

This paper addresses the design considerations involved in the conversion of a gasoline powered vehicle into an EV, considering a discussion of the various design elements in the conversion, mainly, the characteristics of the original vehicle, the electric motor and respective controller, and the energy storage system.

II. STANDARDS TO LEGALIZE ELECTRIC VEHICLES IN PORTUGAL

In Portugal, to change an ICE vehicle into an EV is necessary the approval of the IMTT (*Instituto da Mobilidade e dos Transportes Terrestres*), according with the article number 115 of the road code. The more relevant aspects in the conversion are presented below:

- All the systems of the original vehicle that are changed in the conversion should continue to satisfy the technical requisites applied, e.g., braking system, steering, noise, seat fixation and belts;
- The final weight of the vehicle after the conversion cannot exceed the maximum permissible weight by the manufacturer, however, it is necessary to execute mass tests and brake tests on the converted vehicle. So, if the weight of one axis is higher than the admissible, the vehicle should be submitted to a new approval by the vehicle manufacturer;
- The mounting of the electric motor cannot be performed by removing or weakening any of the structural elements of the vehicle;
- The power of the electric motor cannot be greater than the power of the original internal combustion motor;
- In the vehicles that have vacuum brakes and assisted steering, it must be installed an electrical system that allows the efficient performance that meets the legal requirements;
- The vehicles that have demisting systems to windscreen, whose operation depends of the ICE, it must be installed an electric system with identical capacity to the original;
- It cannot exist a direct contact with the electric system elements that have voltages greater than 60 V (DC) or 25 V (AC). The protections should be fixed securely, should be mechanically resistant, and only can be removed with the aid of tools;
- The batteries must be fixed to the vehicle structure in order to avoid movements and to ensure electrical isolation of the chassis. When the batteries are placed in closed boxes it must be provided a forced ventilation system to the outside. The ventilation shall act during the

vehicle operation (batteries discharging process) as well during the charging process. In this circumstance, the boxes must have an indication of the nominal voltage and the chemicals products that constitute them;

- When the vehicle is plugged into the electrical grid to charge the batteries, it must not be possible to place the vehicle in operation.

III. ELECTRIC VEHICLE ELEMENTS

In this item are described in detail the main elements of the conversion of an ICE vehicle into an EV. For this goal, this item is divided in four parts: the electrical motor used; the developed controller; the batteries of the energy storage system; and the developed charging system.

A. Electric Motor

There are several types of electric motors that can be used in EVs. Essentially, these motors could be divided in two main types: the Direct Current (DC) motors; and Alternating Current (AC) motors (Fig. 1). Both types of motor have advantages and disadvantages and the selection should be made in accordance with the required performances for the vehicle, like nominal power and peak power.

Nowadays, there are mostly used four types of motors for the EVs conversions, that are: DC Motor (DCM); Induction Motor (IM); Permanent Magnet Synchronous Motor (PMSM); and Switched Reluctance Motor (SRM) [2][3]. The DCM is the electric motor that is more used in conversions, however, for the presented conversion it was chosen a Permanent Magnet Synchronous Motor with axial flux, of a type denominated: AFIR-S motor (Axial Flux slotted Internal Rotor external Stator Permanent Magnet motor). The selected AFIR-S motor is presented in Fig. 2. The main characteristics of this motor are shown in Table I. This motor is composed by one internal rotor and two external laminated rotors with radial orientation of the slots (Fig. 3). The AFIR-S motor has some advantages over the other electrical motors that can be used in conversions similar to the presented in this paper [4][5]. The main advantages that influenced the choice of this motor are:

- Reduced rotor losses, the rotor uses magnets;
- Reduced engine size for the same power value, when compared with other types of motors;
- Wide features adaptation to the project specific needs, due to the available variety of magnets arrangements;
- High efficiency.

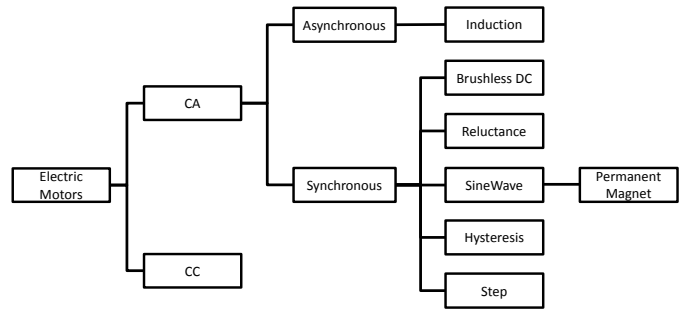


Figure 1. Types of electric motors to use in EVs.

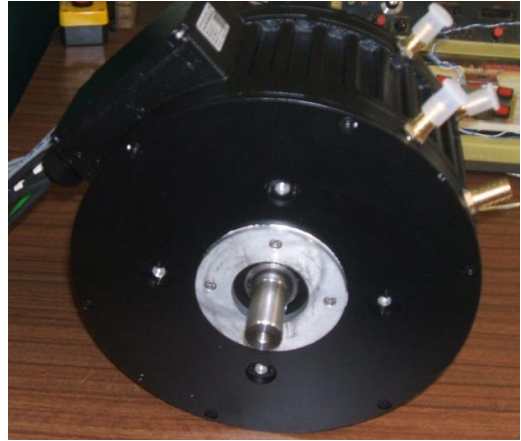


Figure 2. AFIR-S motor used in the presented EV conversion.

TABLE I. AFIR-S MOTOR CHARACTERISTICS

Characteristics	Value
Nominal Power (P_N) [kW]	30
Stator Winding Connection	Y
Nominal Voltage (V_N) [V]	187
Nominal Current [A]	113.5
Speed [rpm]	6000
Voltage constant (k_e) [V/1000 rpm]	42.1
Torque [Nm]	47.7
Number of Poles (p)	8
Nominal Frequency [Hz]	400
Stator Resistance (R) [$m\Omega$]	26.3
Inertia (J) [$m.kg.m^2$]	5.86
Weight (m) [kg]	29.6

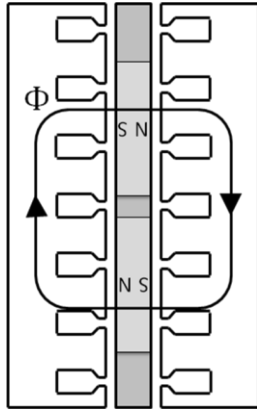


Figure 3. Topology with flux direction of the AFIR-S Motor.

In Fig. 4 are shown the curves of the AFIR-S motor that relate the nominal Torque (M_N), the peak Torque (M_{peak}), the Power (P), and the speed (n/n_N). Analyzing these curves it is possible to define an approach to the behavior of the EV, namely, the maximum speed in function of the consumed power. In an early stage of the conversion these curves are also extremely important because with them it is possible to implement precise simulation models, for a more efficient implementation of the electric motor controller. Taking into account that this motor is water refrigerated it was necessary to install a water pump. In order to dissipate the heat of the water, it was used the original cooling system of the vehicle.

The AFIR-S motor characteristics are also important to define the batteries bank capacity, which will define the distance that the vehicle will be able to overcome with a single batteries charge. In this way, it is necessary to establish a relationship of compromise between the required vehicle autonomy (expressed in terms of the batteries bank capacity) and the batteries bank size and weight.

B. Developed AFIR-S Motor Controller

There are several sellers that have controllers for the large variety of electric motors for EVs, which allow the control of the torque and the speed, through different control techniques. However, for the electric motor used in the presented conversation (AFIR-S motor) there are not too many manufacturers developing controllers. So, it was developed a controller laboratory prototype, aiming the specifications of this motor. As shown in Fig. 5, this controller is divided in two parts: the Power Converter and the Digital Control System.

The Power Converter is composed by three IGBTs modules (each module has two IGBTs), with respective drivers circuit, by snubber capacitors. The DC bus is composed by 17 batteries (12 V, 33 Ah) in series, and by 10 capacitors (each one 1 mF - 450 V connected in series and parallel) in order to obtain 2.5 mF – 900 V.

The Digital Control System is composed by the DSP (Texas Instruments TMS320F2812), the signal conditioning circuit (that receives the currents and the voltages signals from the sensors and adjust these signals to the voltage range of the ADCs), the circuit that receives the accelerator and brake

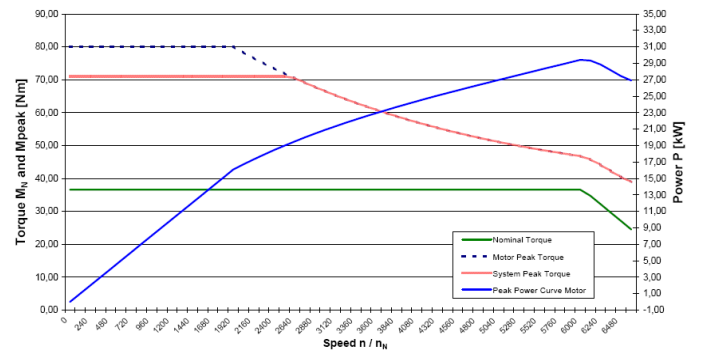


Figure 4. Curves of the AFIR-S motor that relate the nominal Torque (M_N), peak Torque (M_{peak}), Power (P) and the speed (n/n_N).

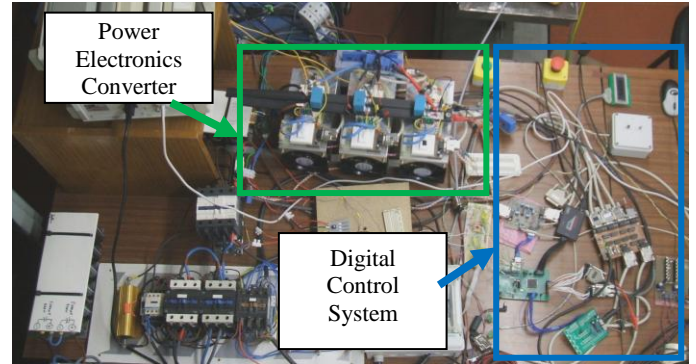


Figure 5. Developed AFIR-S motor controller: Power Electronics Converter and Digital Control System.

position signals, the signals from the charging system, and the type of selected operation (related with the EV operation). Taking into account the signals received by the DSP, it performs the necessary calculus to generate the pulses to the IGBTs, in order to control the Power Converter operation.

C. Batteries

The electrochemical batteries are used in EVs to store the energy received from the electrical grid and to deliver this energy to the vehicle movement when it is required. Nevertheless, the EVs batteries can also be used in conjunction with other energy storage systems, such as ultracapacitors, aiming to store energy during transient moments, as during the regenerative braking. Theoretically, the batteries are able to store the energy received indefinitely and they can provide this energy when it is required without constrains. From this point of view, the batteries only exchange energy between systems, and during this energy transformation process (batteries charge and discharge processes) always occurs losses, mainly by heat.

For EVs, the batteries are the main source of energy, and consequently it is necessary a weighted choice of the batteries aiming their performances, mainly, the large Depth of Discharge (DoD), processes of charging and discharging with high currents, and a large number of cycles with the same initial characteristics, i.e., large lifespan when are respected their nominal characteristics (the lifespan is strongly influenced by the charge and discharge processes, and respecting these

processes, it is possible to reach the maximum reliability for the batteries).

Regarding the distinction between batteries for EVs there are many studies developed [6] and the distinctions are made, among others, through the chemical elements (as lithium, nickel or lead-acid), by the inherent cost, the energy density (the capacity to store energy in relation to the volume), power density (the power in relation to the volume), the number of charge and discharge cycles, the allowed temperatures and the maximum currents allowed for charge and discharge. For EV applications, these parameters are extremely important because they influence the overall behavior of the vehicle.

Aiming to maximize the vehicle efficiency but also to minimize the costs of the EV conversion described in this paper, it were used 17 Absorption Glass Mat (AGM) batteries of the Power Mobility Series, with 12 V and 33 Ah each one. These batteries were connected in series in order to obtain a bank of batteries with 6.7 kWh. These batteries have 50% of DoD for 1100 cycles, they are 100% recyclable. They can be used in any position (except upside down) and they are resistant to high temperatures and high vibrations [8].

In the presented conversion, the batteries were placed in the vehicle in two groups, one group (12 batteries) are located in the fuel tank place (Fig. 6 (a)) and the other (5 batteries) at the front of the EV surrounding the electric motor (Fig. 6 (b)). This distribution was made in order to distribute the batteries weight in the two axes without exceeding the maximum weight in each axis.

D. Developed Batteries Charging System

In order to charge the batteries it was developed a laboratory prototype of a bidirectional batteries charging system. This prototype is shown in Fig. 7. This charging system allows the charge of the EV batteries with the correct algorithm, aiming to preserve the batteries lifespan, and with sinusoidal current consumption and with unitary power factor, this is denominated Grid-to-Vehicle (G2V) process. The same system also allows delivering back to the electrical power grid part of the energy stored in the batteries, this is denominated Vehicle-to-Grid (V2G) process. By security reasons during both processes the EV operation is disabled [9][10].

IV. ELECTRIC VEHICLE ASSEMBLAGE

In this item are described the performed steps during the conversion. Initially, are described the main characteristics of the original vehicle, and then is described the electric motor assemblage in the vehicle.

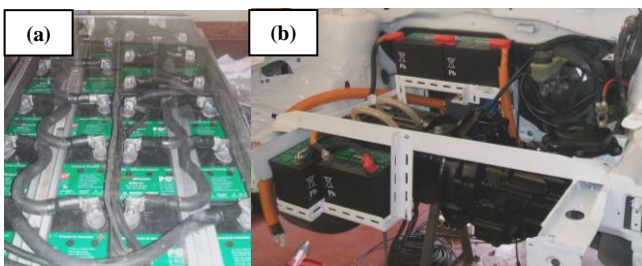


Figure 6. Batteries used in the vehicle: (a) Box of batteries to assemble in the place of the fuel tank; (b) Batteries in front, surrounding the electric motor.

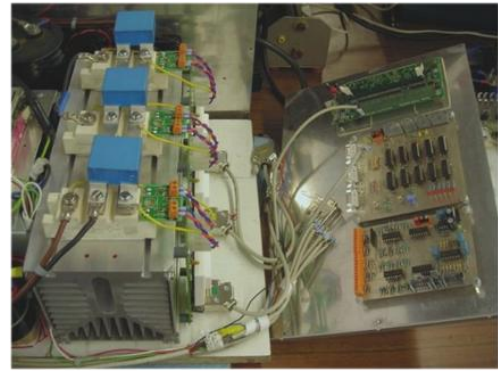


Figure 7. Developed bidirectional batteries charging system.

A. Vehicle Used for the Conversion

To the conversion of the ICE vehicle into an EV was chosen the Volkswagen Polo 1.0L, shown in Fig. 8. This vehicle was chosen because it has not assisted steering and the relation between the tare weight and the gross weight permitted by the manufacturer presents a high difference.

Taking into account that the acquired vehicle has vacuum braking system it was necessary to install an electric vacuum pump. For this presupposition, it was analyzed the vacuum pump characteristics, aiming the lowest possible power consumption keeping the same characteristics of the original system.

B. Electric Motor Assemblage in the Vehicle

In the conversation of ICE vehicles into EVs, the electrical motor can be assembled in several ways. If it is used only one motor it can be assembled at the vehicle front or back, on the other hand, if are used several motors (more than one), they can be assembled at the vehicle front, at the back, or in both places. Taking into account that the original vehicle has the motor at the front, in the presented conversion the electric motor was also assembled at the front. In Fig. 9 are presented some of the possibilities that can be adopted to place the electric motor at the front of the vehicle. These possibilities are described below:

(a) This topology is composed by an electric motor (M) connect to the direction of the vehicle through the clutch (C), the gearbox (GB), and the differential (D). This configuration is mostly used because it only changes the combustion engine by the electric motor.

(b) This topology is similar to the previous one, in which it is removed the clutch and fixed the gearbox (GB), it is denominated fixed gearing (FG).

(c) Unlike the previous topologies, in this topology the electric motor (M) is connected directly to the differential (D) without gearbox (GB) or fixed gearing (FG).

(d) In this topology are used two electric motors (M) connected each one to the front wheels, once more without gearbox (GB) or fixed gearing (FG).

(e) This topology is similar to the previous, but between the electric motors (M) and the wheels are used fixed gearings (FG).



Figure 8. Volkswagen Polo ICE vehicle that was converted into EV.

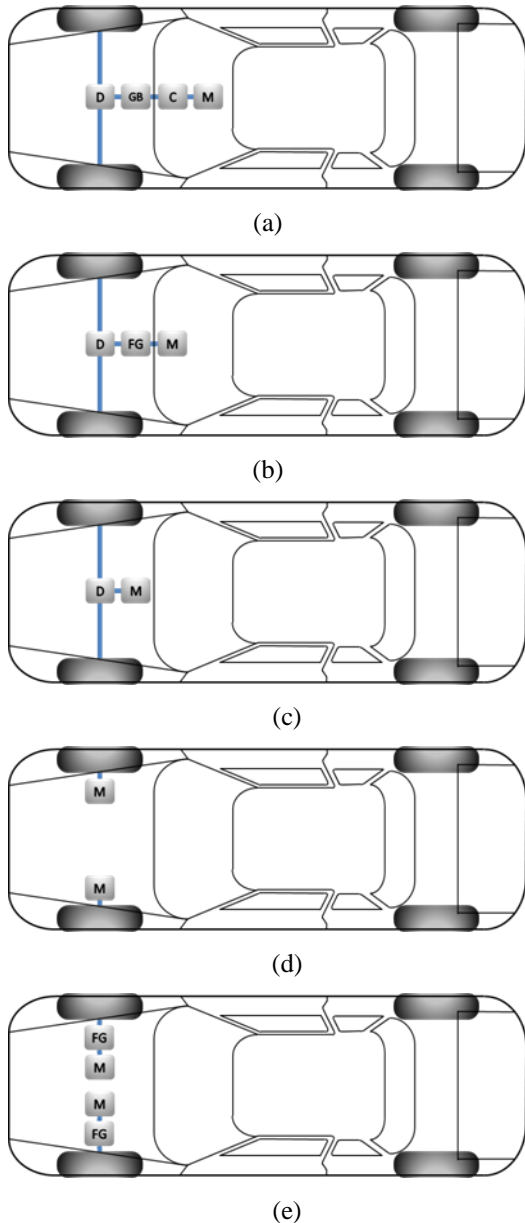


Figure 9. Topologies to assemble the electric motor at the vehicle front.

In order to avoid a very elaborated and difficult to implement conversion project, it is advisable to only adopt one of the topologies (a) or (b). In the presented conversion was used the topology described in (a), because it is only necessary to change the internal combustion engine by the electric motor. For this type of conversions this is the most used topology.

C. Final Overview of the Vehicle

In Fig. 10 is presented the final aspect of the electronic systems implemented and installed at the front of the vehicle. In this figure is shown the power converter and the digital control system of the electric motor controller. As referred before, the electric motor was placed at the vehicle front; however, it was placed below the electronics and is not visible in this photography.

V. CONCLUSION

The conversion of a traditional Internal Combustion Engine (ICE) vehicle into an Electric Vehicle (EV) is presented in this paper. This work, and the technology developed on it, aims to contribute to the widespread use of EVs in the new transportation paradigm. In this sense, it was briefly described the more important parts of the conversion, of the original vehicle, the Axial Flux Permanent Magnet electric motor and its controller, and the batteries. It is important to emphasize that, to the presented conversion were developed laboratory prototypes of the electric motor controller and of the batteries charging system, based on power electronics converters and on digital control systems. Currently, the converted EV is being tested in order to improve the developed controller, and it will be developed a regenerative braking system, as well as a fast charging system to the batteries.

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Figure 10. Final aspect of the electronic systems (power electronics converter and control system) implemented at the front of the vehicle.

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