ELECTRIFICATION OF THE LOW COST COMPETITION VEHICLE. A PARADIGMA CHANGE

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1.- INTRODUCTION

Since the beginning of the 21st century, concern for the environment and its deterioration, due to high levels of energy-related pollution and greenhouse gases, has widespread in the population and different administrations and governments at all levels, from the international to the local level. This has improved social awareness to the fact that there are already numerous measures, taken by governments and institutions, that seek to reduce and/or alleviate the actions arising from such pollution and therefore the energy consumption associated with fossil fuels. One of the highest levels of localized pollution, guilty of high levels of CO emissions$_2$No$_X$ and particulate matter, among others, is the transport sector, and more specifically those vehicles equipped with internal combustion engines (ICE).

Along with the emergence of monitoring techniques [1] and preventive measures of the effects of pollution, such as efficient driving techniques [2], alternatives arise to minimize emissions and discharges. In addition, it is important to note that there are numerous current options that are an alternative to internal combustion vehicles. Among them are the increasingly popular solutions based on electric powertrains used in hybrid or purely electric systems, either with energy accumulated in batteries or hydrogen. All this makes the European car fleet warmly changing.

In any case, current strategies are limited not only to the change of engine but to a decrease in the total energy consumed [3]. In this field it is important to cite the efforts made in minimizing passive resistances [4], as well as in structural optimization to reduce vehicle weight without affecting active [5]-[8] or passive [9]-[11] safety. The technological development of new powertrains includes other options in traction systems that allow to optimize performance such as wheel motors [12].

This work delves into the use of these new powertrain technologies in the world of motorsport racing. An application is proposed to a vehicle of the category of Hill Climb, taking as reference an existing vehicle with an ICE, of reference in the sector.

2.- MATERIALS AND METHODS

Today, more and more manufacturers are dedicating design and/or productive efforts to developing electric vehicles, either from a redesigned model or starting a new one. Some applications that can be listed are "last mile" freight transport networks or urban passenger transport networks. Other applications are linked to high-end vehicles and racing vehicles.

For the electrification of a vehicle, a model used in the "Hill Climb" mode has been chosen. Within motorsport, the Hill Climb is regulated by the International Motorsport Federation (or FIA), as a discipline in which vehicles travel distances of between 1 and 10 km, with large slopes, usually along mountain roads. This work is based on the electrification of a vehicle (Figure 1) with multi-tubular carbon steel chassis, fiberglass body and 4-cylinder 1000 cm^3 engine, with a power of 200 hp (150 kW).

Fig. 1. Vehicle in mountain climbing competition from Spanish manufacturer BRC (https://www.bangoracingcars.com/B49.html).

After studying the technical characteristics of this type of vehicle, it is decided that the modification will focus only on modifying the elements that store the energy and generate the power. It is estimated that the components needed to perform the conversion and, ensuring proper operation of the new prototype, can be placed at the rear of the vehicle. This being the place where the components of the current system are located, the problem of displacement the center of gravity of the vehicle is avoided. If it is of interest to optimise the suspension or steering systems for the new mass distribution, the appropriate parameters and sensitivity to the changes to be made [13] should be analysed. These developments should take into account all aspects related to kinematics and three-dimensional dynamics [14], as well as the performance of the different suspension and steering elements. Currently this design and optimization process is carried out using tools that allow testing on virtual prototypes with the consequent saving of resources.

In this case, the solution of a single motor is presented which, through a self-locking differential, distributes the movement to the two rear wheels. As restrictions of this work it has been proposed to maintain the performance of current vehicles with a new 100% electric powertrain trying as far as possible to reduce the cost of investment necessary to meet these requirements. Structural modifications and/or fairing of the vehicle will also be avoided, thus maintaining its already known and proven driving performance and responses, also avoiding modifying its aerodynamic response.

Another fundamental aspect, and indispensable to maintain for the viability of these vehicles, is the range. Currently, their fuel tanks allow them to perform between 1 and 2 full stages of climbing. A battery pack must be searched that stores enough energy to allow the rise of 2 stages, avoiding the need to charge them between them.

Once the vehicle has been defined to be electrified, a design must be made based on a route (test), with the aim of maintaining the performance of the internal combustion vehicle. These benefits are summarized in the criterion of the competition, which is the time spent in going through the stretch. Taking into account the premises of a low-cost transformation, development based on a 4x2 traction design is opted for, as the original vehicle has. An motor with known performance is chosen, which has adequate torque and power values and the battery pack is sized to ensure that the total accumulated energy is adequate to cover the three sleeves of a type test. The electric motor shall be a permanent magnet motor with at least the following characteristics:

- Maximum power: 120 kW
- Maximum torque: 350 N/m
- Maximum speed: 12000 rpm

A multi-object methodology is applied for the design of the transformation to electric vehicle [15]. In this case it is proposed that the variables to be optimized are the battery assembly mass and the final transmission ratio between the motor and the differential. As a basis for the development of the electric vehicle's powertrain, a test of the European Hill Climb Championship has been taken. This route is located in Northern Spain, more specifically in Asturias. The international climb to Fito (Figure 2) is an international test carried out during the month of May in the Sierra del Sueve. It is collected among the qualifying tests for the European Hill Climb Championship.

Fig. 2. Image of the stretch in a digital terrain model.

From a technical point of view, the test has the following characteristics:

- Overall length: 5320 m
- Maximum slope: 6.65%
- Average slope: 5.96%
- Output height: 48 m. n.m.
- Goal height: 366 m. n.m.

The test is divided into 2 timed stages and count for the final classification. The proposed methodology uses a multi-object genetic algorithm that is based on the following data and premises:

- Regarding the vehicle: All geometric, mass and inertial parameters of the chassis and body, such as total mass of the vehicle without the battery pack, wheelbase, track widths, effective wheel radius, center of gravity position, are considered as known. Also known are the characteristic values of the motor (torque and power) and its maximum turning speed.
- Relative to route: The test path has been divided into a set of sections. For each of the sections the following values are known: start and end (measured on the axis of the track, having as its origin the "Output" of the test), radius of curvature (considered infinite in the case of straight section), slope, maximum tire-road friction coefficient (both longitudinal and transverse) and possible limited maximum speeds in some section.

In addition, the reference time is set and limitations are determined in the maximum traction/braking and lateral acceleration.

The characterization of the track is done by a digital terrain model from a Geographic Information System (GIS) that is processed in combination with cartographic collection of orthophotographs of the plot. In this case, information from a low-cost data capture system is based [16] installed in an instrumented vehicle equipped with a combustion engine. If any of the values required in the study cannot be measured, it can be done by estimating [17] using multibody simulation tools.

Pre-study of the road using the instrumented vehicle [18], allows to analyse the route and potentially dangerous points at which the demand for propellant performance must be limited. As the proposed optimization methodology is developed, it is intended to ensure the performance of the vehicle by knowledge of the adhesion values available in each section [19]. This allows the mutiobjetive genetic algorithm to take the vehicle to the maximum of its dynamic performance, including the possible speed limitations indicated by the organization of the event in a specific section depending on the special safety conditions [20].

Once the optimized powertrain assembly has been obtained, the complete design of the vehicle is performed. There have been several design iterations needed to find the current and optimal solution for project status. Finally, the design is based on a schema in which the elements are serially matched (Figure 3). It is based on the use of an electric motor, controlled and connected to an inverter. This one is energized by a battery pack that will have a BMS. All this will be cooled by its corresponding refrigeration systems. Braking will be carried out by the original hydraulic system, not including an energy regeneration. In the case of those commercial components, a list of possible options that fit what is proposed will begin to be collected. Once collected, the one closest to what is searched according to the different selection parameters will be selected.

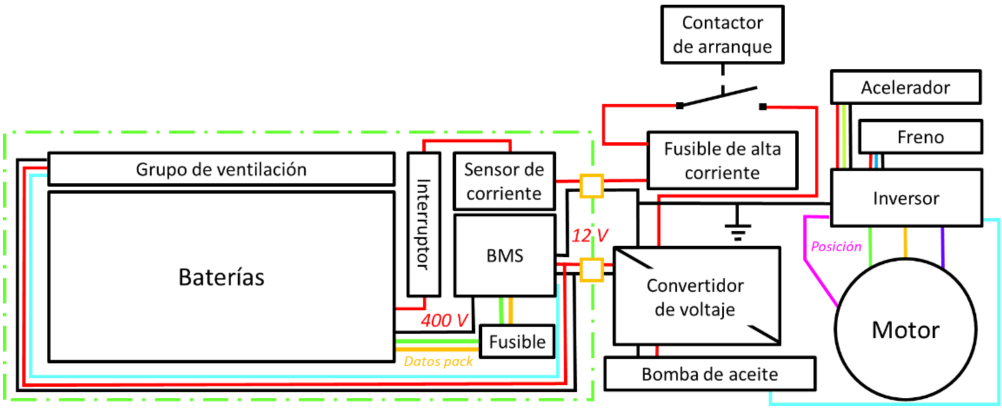

Fig. 3. Proposed scheme for the new electric powertrain.

As a result of the interpretation of the scheme set out above, the following operation of the powertrain is apparent.

- The system is divided into 4 main subsystems, the energy storage and transport elements (battery pack) represented within a green dot line as well as the conductive elements, power elements where the motor is mainly included, control elements among which the inverter stands out although it could also be classified into power elements and auxiliary elements, responsible for aspects such as cooling, safety, interface, inputs/outputs, among others.
- The battery pack stores the energy, which must be charged externally through an external charger (this eliminates the weight of an extra unnecessary element during the competition).
- Each of the cells must be monitored independently in the temperature and voltage parameters, these being controlled by the BMS.
- The energy of the cells flows through aluminum/copper plates, which make up the power bus, which end in two power cables. These go through two safety elements (fuses, ICPs, switch, etc.).
- The current generated by the battery pack comes out through two conductors towards the continuous and alternating inverters.
- From the voltage converter, a voltage line at 12 V is generated that feeds auxiliary elements (Pumps, ventilation, BMS, inverter control line, etc.)
- From the alternating inverter, the 3 three-phase lines that feed the motor come out.
- The cockpit data lines and motor feedback arrive at the inverter.

3.- RESULTS

The design is composed of a set of elements mounted on a multi-tubular frame, very similar to the ICE vehicle. The choice of a series of commercial components has been chosen with an optimal balance between performance and price. In the case of the motor, after comparing the viable options, the most economical model (10000 euros approx.) and with better performance is the HVH 250-090 of the BorgWarner house. It is an AC motor with extensive use in the project of electric conversions of classic sports cars for its availability, power, speed, weight, cooling, etc.

- ✓ AC voltage: 350 V
- ✓ Peak power: 175 kW
- ✓ Maximum torque: 350 Nm

- ✓ Top speed: 12000 rpm
- ✓ Mass: 40 kg

When selecting a suitable inverter, capable of powering the selected motor it is noted that the output voltage of an inverter is a function of the voltage at the input of the inverter in direct current (DC) as well as the performance. According to the different models on the market, the cost and performance model that best suits the needs indicated above will be the HV-500 model of the Drive Train Innovation house. It is widely used in SAE formula racing vehicles, has a relatively low cost compared to the main competitors in the present range.

One of the critical components of an electric vehicle, which largely define the vehicle's behavior, performance and/or limitations, is the battery pack. For selection, the parameters of the installation must be defined in terms of energy-related aspects. Based on these criteria, the one offered by the manufacturer Energus is chosen as the best option. In particular, the Li8(2x4)P25RT, a model with high discharge ratios of up to 360 Amps, has been chosen. The chosen battery pack is:

- ✓ Serial units: 112 pcs/row
- ✓ Rows in parallel: 1 row
- ✓ Total mass: 47.82 kg
- ✓ Total cost: 7,616.00

For the proper use of lithium batteries, it is essential to have a system for managing the charge and discharge of lithium batteries. After a market study, it is decided to select as the optimal model, the BMS G1 of the EMUS house. It has suitable qualities, being necessary a single module with an affordable price (2,300,00 euros).

Within the subsystems necessary to ensure the proper functioning of the system as a whole, are the two independent liquid cooling circuits. On the one hand, there is the oil cooling circuit (which also acts on lubrication) of the electric motor. On the other hand, there is the cooling circuit of the inverter, in this case water-cooled. Both devices feature real-time temperature sensorization, allowing the control to act as a thermostat by handling the performance on the pumps.

As a result, Figure 4 is shown, depicting the designed multi-tubular frame and powertrain.

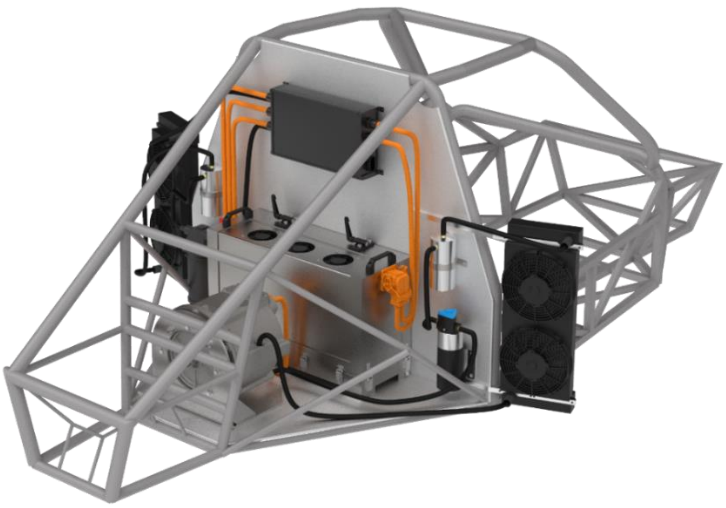

Fig. 4. Image of the design made. It depicts the multi-tubular frame and the elements of the electric drive

4.- DISCUSSION

The scope of this work is the technical definition of the elements necessary for the electrification of the powertrain of a racing vehicle. Development begins with the sizing of the power and energy required for the powertrain system based on available data from ICE vehicle in a particular European Hill Championship test. Once the performances were defined, the state of art analysis and market studies were carried out for the selection of possible commercial candidates of the required elements.

The electric motor was selected as the first element, which defines the rest of the subsystems. The battery was shown as one of the most demanding elements in the design. A complete functional battery pack model is proposed and meets the required requirements.

Taking into account the motor and the battery pack, the rest of the components were chosen, ending with the lay-out of all these components in the chassis chosen as the base.

The following points can be considered as future improvements:

- Redesign and optimization of the battery pack, reducing and/or minimizing its size and weight by considering other emerging technologies.
- Selection of a new motor capable of meeting the indicated performance, reducing its cost.
- Optimization of the cooling system, a second iteration could improve the performance of the cooling system by adapting it to the elements to be refrigerated.
- Heating system design, intended for the preheating of battery cells, in order to improve performance in the first instances of the stage.

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