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Scooter's Electric Motor Characterization and the Sizing of a PEMFC Power Plant Required for its Operation

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ABSTRACT

The development of power plant prototypes based on PEMFC´s for a particular application has important technical and economical impacts on the practical implementation of this technology. In this study, the characterization of an electric motor of an E-Z rider model Scooter was performed aiming at determining the load and therefore, the power demand required under specific operating conditions: no-load, with load and during sudden full stop breaking due to overload conditions. The characterization was performed under two operating modes, i.e. low and high speed modes. Results show that the minimum power required for the low speed, no load operation is 48 W, while maximum power reaches 84 W for operation at high speed with load. Also, maximum power during sudden breaking was limited to 84 W as the Scooter's control system allows for a maximum consumption of 7A at 12V.

The second part of the work presents the methodology used for dimensioning a fuel cell stack that will provide the power for the motor to fulfill load requirements. Simple calculations are based on polarization curves of a 90.5 W fuel cell stack. Accordingly, a $50cm^2$ area and 20 cell stack can provide 84W of power plus a 20% extra power for auxiliaries required in the power system. To maintain higher efficiencies in the conversion of hydrogen while meeting power requirements, it was established that 0.615V per cell at an operating current density of $0.16A/cm^2$ fuel cell stack is adequate for the application.

Keywords: Scooter, PEMFC dimension, electric motor characterization.

1.- Introduction

During the last years PEMFC´s have outstood from other types of fuel cells due to their advanced technology development [1], as well as their flexibility to accommodate many different applications , from portable devices such as mobile phones to stationary applications [2,3]. On the other hand the increase in number of personal vehicles and therefore the increase of pollutant gas emissions from transport activities [4], as well as the constant increase of fossil fuel costs [10], is taking our society to search for newer and better mobility concept alternatives.

In México there are more than 32 million vehicles registered for use on the roads [11], most of them used in big cities which concentrates their use in urban areas causing large traffic jams aggravating the problem [4], resulting also in waste of time and an excessive consumption of fuels. Individual transport alternatives, such as bicycles, motorcycles and scooters offer advantages over more conventional means of transport. Among those benefits we can mention shorter transfer times, less space on the roads, an increase in potential alternative routes and most importantly less power required [5,6]. Using PEMFC technology on this transportation alternatives represent an additional advantage, by eliminating completely the harmful emissions including green-house gases [6,7].

Implementing PEMFC technology as power generators, using hydrogen as a fuel, still represents opportunities to overcome technical engineering challenges [8], that could help improve the extensive use of this technology.

In this work, the electrical characterization of a scooter E-Z rider model electric motor was realized in order to evaluate current demand under some load conditions. Also, a methodology for designing a PEMFC stack for this particular application was carried out. Results for both activities are presented.

2.- Methodology

2.1.- Scooter’s electric motor characterization

The characterization of the engine consisted in determining the current consumed by this under different load conditions. To do this, an array consisting of electric motor, Hall-type sensor, power supply, data logger, processor and power source was joined. Prior to the characterization of the engine, the Hall sensor calibration was carried out by a circuit similar to that described above, in which the scooter was replaced by an electronic variable load. The following sections describe the experimental approach of these activities.

2.1.1.- Sensor Hall-type calibration (Hawkeye® H970HCB DC current sensor)

The calibration test consisted in feed a known current to an electronic load (electronic Load of Heliocentris EL 100) (see figure 1a). When a current is passing through the Hall sensor, it generates a voltage signal associated with it (product of magnetic field strength and the current that is flowing) that is read by the data acquisition system

(PCS10/K8047 Velleman Instruments) and sent to the processor. The data sample consisted of 11 current values between 0 and 6 A, of which the data logger read a total of 1024 values. From this data (V, voltage signal) and the current consumed by the load, a linear regression was used to generate continuous function of the type $I = mV + b$.

2.1.2.- Current consumption test of the Scooter´s electric motor

This test consisted in determine the amount of current demanded by the engine for its two modes of operation (low and high speed) and under the following conditions:

- Without load
- With load (a person of 80 kg)
- Sudden braking of the motor (overload)

For the test were connected to the motor scooter two 6V batteries in series (see Figure 1b). The motor power cord was passed through the Hall sensor for measuring the current consumed, the voltage signal emitted by the Hall sensor was sent to the data processor via the data acquisition system.
The continuous function determined in the Hall sensor calibration was used to calculate the amount of current consumed by the motor, this as a function of the voltage generated by the sensor.

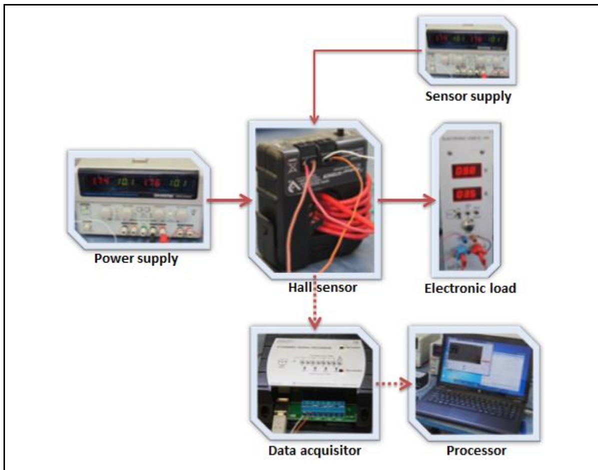

Figure 1a. Connection diagram for the electrical arrangement for calibration of Hall sensor.

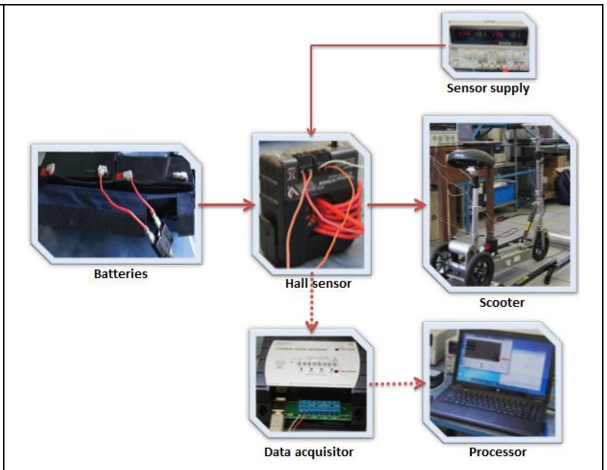

Figure 1b. Connection diagram for the electrical arrangement for the scooter´s electrical motor characterization.

2.2.- Stack fuel cell´s dimension

2.2.1.- Polarization curve

Initial information on designing a fuel cell stack is the steady state polarization curve, which can be a theoretical initial curve or an experimental curve. This curve describes the fuel cell stack performance in particular, it represents the voltage-current density (*V vs i*). An experimental polarization curve is the most reliable information to perform the size design [9], as it represents the actual performance of a system accounting for all implicit voltage loses. Nevertheless, not having an experimental set of data should not be a barrier to determine a fuel cell stack capacity, as the theoretical polarization curve calculation is very useful and reasonably accurate if other experimental information is taken in consideration:

$$E_{FC} = E_{r,T,P} - \frac{RT}{\alpha F} ln\left(\frac{i+i_{loss}}{i_0}\right) - \frac{RT}{nF} ln\left(\frac{i_L}{i_L-i}\right) - iR_i \qquad \text{Ec. 1}$$

where:

E_{FC}, is the cell potential (*V*)

$E_{r,T,P}$, is the reversible potential at given temperature and press (*V*)

R, is the constant gases (*8.314 J mol^{-1} K^{-1}*)

T, is the temperature (*K*)

α, is the charger transfer coefficient

n, is electrons number involved

F, is the Faraday´s constant (96,485 *C mol^{-1}*)

i, is the current density (*A cm^{-2}*)

i_{loss}, are the current losses (*A cm^{-2}*)

i_0, is the reference exchange current density (*A cm^{-2}*)

i_L, is the limit current density (*A cm^{-2}*)

R_i, is the internal resistance (Ohm cm^2)

2.2.2.- Dimensioning method

In this section the sequence of calculations to determine the fuel cell stack capacity is shown. The methodology starts with the maximum current and voltage demanded by the load, 12 V and 7 A, with a total maximum power of 84 W, for this case. These data and the experimental or theoretical polarization curve data should also be considered, these are shown on table 1a and 1b, respectively. In this work the polarization curve data points were obtained from a 20 cell fuel cell stack of 25 cm^2 of geometrical active area, as well as other theoretical data using equation with data shown on table 2. Internal resistance (*Ri*) and limit current density (*i*) were obtained experimentally. On the other hand, the charge transfer coefficient (α) was used to fit the experimental data to the theoretical curve.

Table 1. Polarization curve data

a) Experimental data

*V*c, (V)	Current density (A/cm^2)
0.7573	0.04632
0.725	0.05952
0.67095	0.09948
0.633	0.13948
0.615	0.15964
0.585	0.19956
0.55395	0.23968
0.52615	0.27968
0.5	0.3198
0.489	0.3398
0.4793	0.36
0.466	0.37992
0.4517	0.39992
0.39245	0.43996
0.34865	0.46
0.3267	0.465

b) Theoretical data adjusted to the experimental curve

*V*c (V)	Current density (A/cm^2)
0.883	0.001
0.773	0.025
0.733	0.050
0.703	0.074
0.679	0.098
0.657	0.123
0.637	0.147
0.618	0.172
0.600	0.196
0.582	0.220
0.565	0.245
0.548	0.269
0.531	0.293
0.515	0.318
0.498	0.342
0.480	0.367
0.462	0.391
0.443	0.415
0.420	0.440
0.360	0.464

Table 2 Equation 1 parameters.

Polarization curve parameter [units]	Value
$E_{r,T,P}$ [V], (60°C y a 1 atm)	1.191
R [J mol^{-1} K^{-1}]	8.314
T [K]	333.15
α	0.645
n	2
F [C mol^{-1}]	96,485
i_{loss} [A cm^{-2}]	0.002
i_0 [A cm^{-2}]	3X10^{-6}
i_L [A cm^{-2}]	0.465
R_i [Ohm cm^2]	0.455

This information is used as follows:

a) Cell's efficiency calculation

The cell's efficiency (ŋ), defined as the relation between the energy obtained in form of electricity and the hydrogen energy consumed, is given by:

$$ŋ = \frac{W_{el}}{W_{H2}} \quad \text{Ec. 2}$$

The electricity produced is the product between of voltage and current:

$$W_{el} = I * V \quad \text{Ec. 3}$$

where I is the current in Amperes and V is the cell's voltage in Volts. The hydrogen energy is according to Faraday's law, proportional to the current:

$$N_{H2} = \frac{I}{nF} \quad \text{Ec. 4}$$

where N_{H2} is in *mols^{-1}*, and

$$W_{H2} = \Delta H \frac{I}{nF} \quad \text{Ec. 5}$$

where, W_{H2} is the energy contained in hydrogen and ΔH is the water formation heat, from molecular hydrogen and oxygen:

Liquid water formation: $\Delta H_{H2O\ liq} = -286\ kJ/mol$, then $\Delta H/nF = 1.482$V.
Vapor water formation: $\Delta H_{H2O\ vap} = -241\ kJ/mol$, then $\Delta H/nF = 1.254$V.

Combining equations 2 and 5, the cell's efficiency is directly proportional to the cell's voltage:

$$\eta_{H2O\ liq} = \frac{V_C}{1.482} \qquad \text{Ec. 6}$$

or

$$\eta_{H2O\ vap} = \frac{V_C}{1.254} \qquad \text{Ec. 7}$$

It should be noted that in equations 6 and 7 the sign has been ignored as it does not affect the efficiency estimate.

b) Fuel cell stack voltage

The fuel cell stack (V_{CC}) is determined by the cell voltage (V_C) and the number of cells (N_C) in the stack, (equation 8). Increasing the number of cells also increases the voltage drop due to ohmic resistance. In this work such resistance is not included. Nevertheless, for this work 8 values for N_C were used. Once N_C is known the voltage can be determined (V_{CC}):

$$V_{CC} = \sum_{i=1}^{N_C} V_i = \overline{V_C} \cdot N_C \qquad \text{Ec. 8}$$

c) Cell stack current estimation

The fuel cell stack power (W_{CC}) is an operating parameter associated to the application load and is estimated:

$$W_{CC} = V_{CC} \cdot I_{CC} \qquad \text{Ec. 9}$$

From the equation above, we can obtain the cell current (I_{CC}):

$$I_{CC} = \frac{W_{CC}}{V_{CC}} \qquad \text{Ec. 10}$$

Once W_{CC} is determined a safety factor can be considered to account for auxiliaries or transient specifications so that the cell will have the capacity to provide energy for control, balance of plant (BOP) and even losses during power conditioning. This factor normally is between 20 and 30 % but it is up to the designer to choose the final factor.

d) Cell's geometrical area

I_{CC} is also defined as the product of current density times the active area:

$$I_{CC} = i \cdot A_C \qquad \text{Ec. 11}$$

From this A_C, can be calculated:

$$A_C = \frac{I_{CC}}{i} \qquad \text{Ec. 12}$$

e) Recalculation of data for graphical representation

From equations 7, 8, 10 and 12, cell efficiency ($\eta_{H2O\ vap}$), cell stack voltage (V_{CC}), total fuel cell stack current (I_{CC}) cell's active area (A_C), were calculated for each operating point of the cell's polarization curve (V_C, i) and for each case of number of cells proposed for a cell stack (N_C). Once sets of data are obtained, plots of $V_C\ vs. i$, V_C *vs. Power density* and *Cell efficiency vs. Power density*, as well as A_C vs. V_C, , are built using visual tools ("graphical" design).

f) Design criteria and restrictions

Estimation of V_{CC}, I_{CC} or A_C, for the 8 proposed cases for N_C and combined with 20 points from the polarization curve (table 1b) give a range of 160 possibilities of fuel cell stacks, each with particular features of V_{CC}, I_{CC}, A_C and N_C. Each stack can fulfill the required power but not all will fulfill restrictions related to the target efficiency, the geometrical active area and nominal current and voltage:

I. Cell efficiency: the recommended range is between 45 and 60%. 60 % would be for cases where there are no restrictions for the stack size of the volume provided for it in the particular application. 45 % can be used for the case where these restrictions are tight.

II. A valid restriction that the designer or technical expert can define is the size of the maximum geometrical active area for the stack.

III. If mechanical and structural limitations are light for the stack integration, values of V_{CC} and I_{CC} for the selected case, are recommended to be near the required values for the load, which will allow better efficiencies for power electronics conversion.

IV. An additional restriction can be the establishment of a particular work efficiency.

3.- Results and analysis

3.1.- Scooter´s electrical motor characterization

3.1.1.- Hall sensor calibration

In figure 2a current load values and their corresponding voltage values measured by a Hall sensor. The correlation of measured values showed that there exist a direct relation with a slope and a Y intercept of -0.68 y 7.33, respectively. Figure 3b shows a comparison between experimental values and those calculated with the line equation obtained. Such figure shows a good fit of the experimental data equal or larger than 1.5 A and up to 6 A.

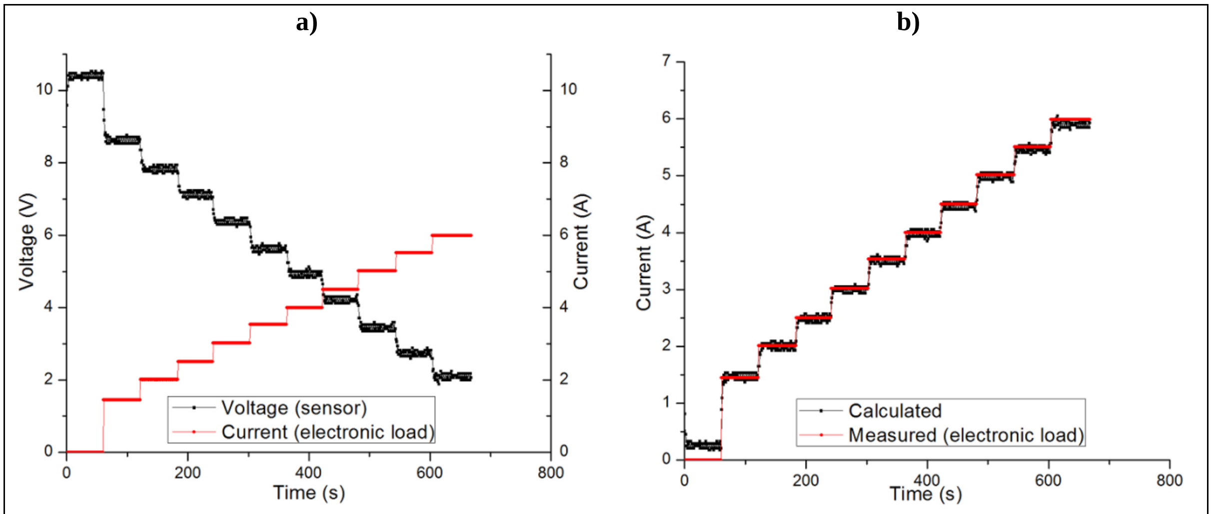

Figure 2. a) Graphic of the sensor signal voltage and current demanded by the electronic load vs. time. **b)** Comparison of the calculated current values by the equation vs. the experimental ones.

3.1.2.- Current consumption test of the scooter's electrical motor

The test for determining power consumption consisted in make work the scooter in the two modes of operation and loading conditions, figure 3 shows the result of this test. The baseline (a) corresponds to the on-state of the scooter but without power demand; the nonzero value read in the graph is due to the deviation of 0.28 A that the equation showed for current values below 1.5 A (figure 2b). The first peak (b) corresponds to the current demand on the low-speed mode and unloaded, in this state the scooter consumes 3.7 A. The test at this same speed but with load, showed a demand for 7 A (peak c). The peak b' and d represents the sudden braking test at low speed; corresponding b' to the current demand without stopping (3.7 A) and d to the demand with sudden braking (7 A). As shown, the load demand in both the test with load and sudden braking the motor´s current consumption is 7 A, apparently the electric circuit of the scooter is limiting the maximum current consumption.

For testing power consumption at high speed, it was found that the demand for no-load current is 4.13 A (peak e), only slightly higher than that consumed in low speed. On the other hand, the test under load showed a demand of 7 A (peak f) and during sudden braking the demand was also 7 A, thus confirming that the electrical control circuit of the scooter is controlling the maximum current. This result indicates that in the sizing process of the stack should be considered as operating nominal current 7 A. Considering also the batteries used as a source gave a voltage of 12 V, then we have that the stack in design process should be able to provide an output of 84 watts plus a percentage for auxiliary systems (BOP) and a factor design safety.

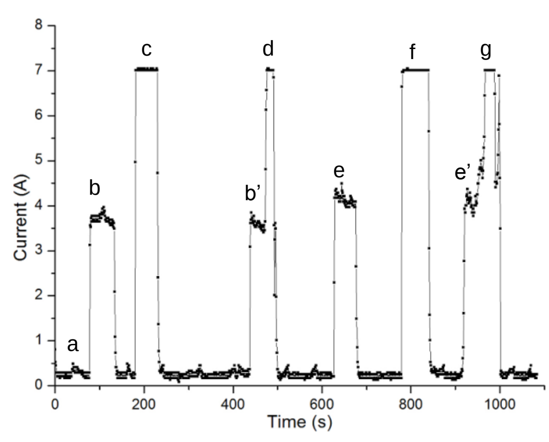

Figure 3. Scooter current consumption at different loads conditions

3.2.- Stack fuel cell´s dimension

3.2.1.- Polarization curve

As discussed in section 2.2.2, the initial information in the design of a stack are the data from an experimental polarization curve or theoretical. In order to show that both the use of experimental and theoretical data is completely valid, figure 4 shows graphs of the polarization curve data presented in tables 1a and 1b, experimental and theoretical, respectively. In this, one can observe the similar trend between the two data sets.

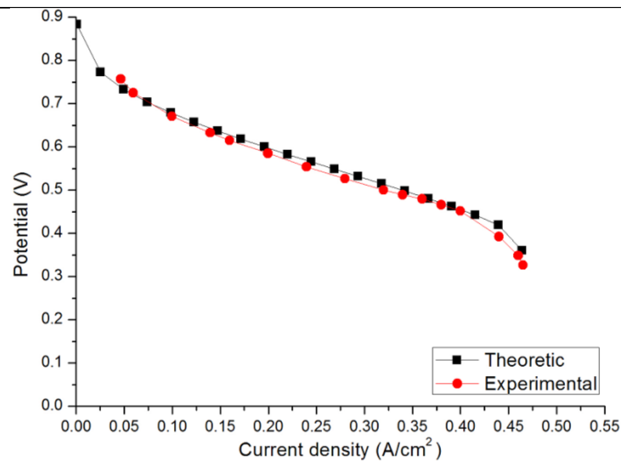

Figure 4. Adjust of the theoretical polarization curve to the experimental one.

3.2.2.- Graphical dimensioning of the fuel cell´s stack

The results obtained in the characterization of the motor scooter was our input information on the sizing process:

I. Current required: 7A
II. Voltage required: 12V
III. Power required: 84 W

The following Nc values were proposed as case studies:

Cases	Nc: Number of cells
Caso 1	5
Caso 2	10
Caso 3	15
Caso 4	20
Caso 5	25
Caso 6	30
Caso 7	35
Caso 8	40

From the value of power required, we calculated the nominal power of the stack given an additional 20%: 100.8 W. Using this value, Nc, and data of polarization curve in the equations 7, 8, 10 and 12, allowed the calculation of the cell efficiency, (ŋ_(H2O vap)), stack voltage (*V*cc), stack total current (*I*cc), and the geometric active area of the cell (*A*c). As mentioned in the experimental section 2.2.2, the combination of *N*c and the 20 points of the polarization curve resulted in 160 possible cases of stack; all of them meet the required rated power of 100.8 W by combining the values *V*dc and *I*cc. From this range of possible stacks, we applied the "Restriction I", related to the cell efficiency interval recommended (used fuel efficiency): 45 to 60%, which represented in the graph Voltage, efficiency Vs. Power density (Figure 5a), can be seen that the efficiency range is equivalent to voltage range between 0.55 and 0.75 V. The representation of this interval voltage on the polarization curve can be seen in Figure 5b.

a)

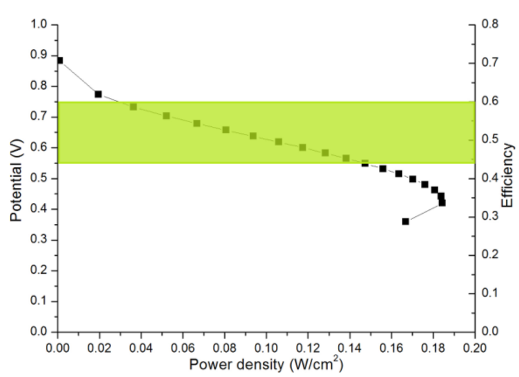

Figure 5a. Visual representation of the recommended efficiency interval in the graphic: *potential, Efficiency vs. Power density.*

b)

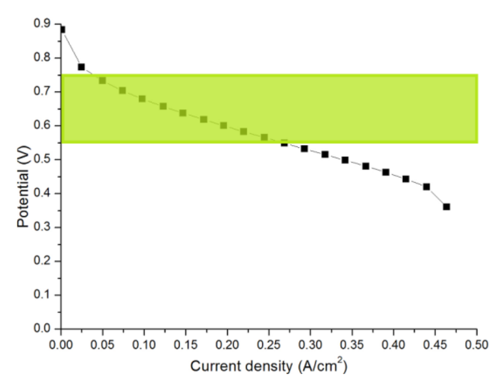

Figure 5b. Visual representation of the recommended efficiency interval in the polarization curve.

The application of this restriction decreases the number of possible stacks to 72. Additionally, in applying the "Restriction II" related to the maximum active area, which in our case is 100 cm^2, limited by the space for the stack on the scooter, the number of cases decreased to 54. In figure 6, the aplication of both restrictions can be observed.

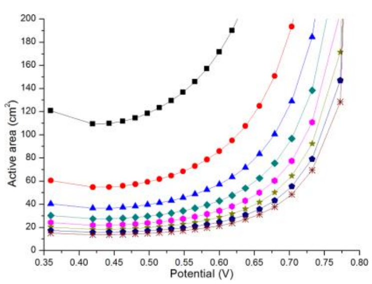

Figure 6a. Graphic representation of the range of initial cases of stack.

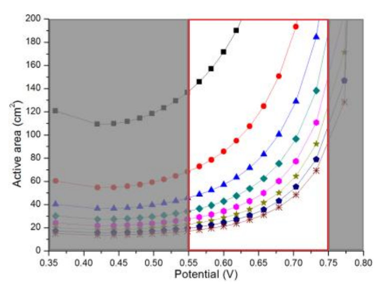

Figure 6b. Application of the restriction I: efficiency interval recommended.

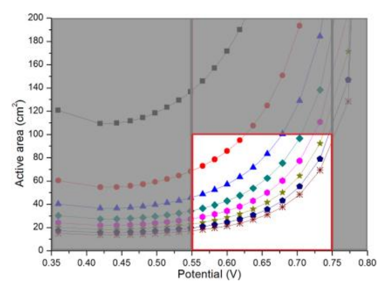

Figure 6c. Application of the restriction II: Maximum geometrical active area.

The 54 cases resulting from applying the restrictions I and II are already cases that could function properly, however, choose any of them, would transfer to the power electronics team the work of adjust the voltage and current required by the scooter. In our case, seeking to have the highest efficiencies in the stages of voltage regulation, the restriction III was applied, in which we stated that the output of the stack may have 7 ± 2 A y 12 ± 2 V. Values falling in these ranges have been highlighted in the tables 5 and 6. Of these, only 7 cases of stack meet both conditions, all in the "Case 4", corresponding to stacks of 20 cells. If after these seven cases apply the "Restriction IV", establishing a fuel usage efficiency of 50%, for example, we have the characteristics of the stack that meets this criterion is between two values:

Geometric active area:	48-54 cm^2
Stack nominal Voltage:	12.37-12.75 V
Stack nominal current:	7.91-8.15 A
Cell’s number:	20

With this we finish the stack sizing process

Table 4. Geometrical active area values (*A*c) after applying the restrictions I and II.

	STACK ACTIVE AREA							
Efficiency	CASE 1	CASE 2	CASE3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
0.584						92	79	69
0.561				97	77	64	55	48
0.542			100	75	60	50	43	38
0.524			83	62	50	42	36	31
0.508			72	54	43	36	31	27
0.493		95	63	48	38	32	27	24
0.479		86	57	43	34	29	24	21
0.464		79	52	39	31	26	22	20
0.451		73	49	36	29	24	21	18

Table 5. Stack voltage values (*V*cc) after applying the restrictions I and II..

	STACK VOLTAGE							
Efficiency	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
0.584						21.977	25.640	29.303
0.561				14.069	17.586	21.103	24.620	28.137
0.542			10.186	13.581	16.976	20.372	23.767	27.162
0.524			9.860	13.146	16.433	19.719	23.006	26.293
0.508			9.558	12.745	15.931	19.117	22.303	25.489
0.493		6.183	9.274	12.365	15.457	18.548	21.639	24.731
0.479		6.001	9.001	12.002	15.002	18.003	21.003	24.004
0.464		5.825	8.737	11.649	14.562	17.474	20.386	23.299
0.451		5.652	8.479	11.305	14.131	16.957	19.784	22.610

Table 6. Stack current (*I*cc) values after applying the restrictions I and II.

	STACK TOTAL CURRENT							
Efficiency	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
0.584						4.587	3.931	3.440
0.561				7.165	5.732	4.777	4.094	3.582
0.542			9.896	7.422	5.938	4.948	4.241	3.711
0.524			10.223	7.668	6.134	5.112	4.381	3.834
0.508			10.546	7.909	6.327	5.273	4.520	3.955
0.493		16.304	10.869	8.152	6.521	5.435	4.658	4.076
0.479		16.798	11.198	8.399	6.719	5.599	4.799	4.199
0.464		17.306	11.537	8.653	6.922	5.769	4.944	4.326
0.451		17.833	11.889	8.916	7.133	5.944	5.095	4.458

4.- CONCLUSIONS

The characterization of the electric motor scooter showed that power consumption is between 3.7 A for the condition "without load" and 7 A for the terms "with load" and "motor suddenly stopping." This result indicated that 7 A is the maximum current allowed by the electrical control of the scooter.

The application of the restrictions I and II of the proposed methodology allowed to identify the possible dimensions of the stack in design, this, in terms of ranges of total voltage, current, total geometric active area and number of cells. This range of options can be reduced to one, if we apply restrictions as the III and IV.

According to the proposed methodology and restrictions, the recommended stack size to supply the power required by the scooter is 20 cells with active area between 48 and 54 cm^2, rated operating voltage between 12.4 and 12.8 V and rated current between 7.9 and 8.2 A.

5.- ACKNOWLEDGMENTS

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