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Energetic Modelling of Ánibal Solar Vehicle for Murcia Solar Race Competition.

N. Gómez[1], J. Lopez-Hellín[1], J. Faxas[1], A. Guerrero[1]

[1] Department of System Engineering and Automation
E.T.S.I.I., Technical University of Cartagena (UPCT)
Campus de la Muralla- C/ Doctor Flemming, 30201 – Cartagena, Murcia – España Tel: 34 968 325536
e-mail: antonio.guerrero@upct.es

Abstract.

With the energetic modelling, we search to make a tool with which to predict a future spending of energy in different races and optimize this energy.

The energetic modelling of Aníbal vehicle is very important for our objectives because it provides a tool that is very useful for our designs. Thanks to modelling we can save time and money because we can make the test of our ideas and designs before spend our resource. Also the modelling is very useful for our pilots due to before the race they can test different ways of driving for to save the maximum energy possible.

Results are very good, in the different graphics we can see that the current, power and energy in the time is very similar to real graphics.

Key words

Energetic modelling, Solar race car, photovoltaic, renewable energy, energy efficiency, electric car.

1. Introduction

A solar race car is an electric vehicle that is lightweight and aerodynamically efficient and it uses the irradiance from sunlight using photovoltaic system to generate its own power for propulsion and for storing in batteries. So with renewable energy this prototype car is self-sufficient and does not damage the environment with pollutions [1].

The electric propulsion system idea in a car is not new. The first electric car was developed in 1838, and there were more electric cars in the streets than gasoline cars until 1930's [1].

There are different challenge for solar vehicles and others experimental cars. And the "SOLAR RACE Región de Murcia" is one of the most famous in Spain. And it is about an efficiency and endurance competition for vehicles powered by alternative energy sources. The objective is to drive the distance using the least amount of energy. And each vehicle must be designed and built by groups of students from education centers. The completion is located in the Cartagena Racetrack [2].

The Ánibal vehicle is an experimental solar car developed in the Technical University of Cartagena (UPCT) by students. Its aerodynamic body is made of carbon fibber and some parts are made of aluminium, titanium and wood. And for its movement uses two wheels in the front for the direction and a back wheel for traction.

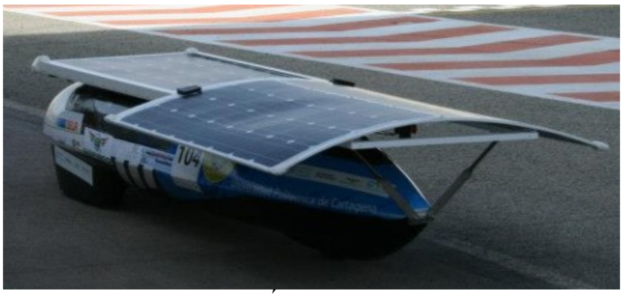

Fig. 1 Ánibal Solar Car

The importance of energetic modelling is based on that it is possible to determine the energy generated by the photovoltaic system, and power consumption of the motor system. And because of the uneven ground in different places and variation of irradiation by month and place, you need to have a method to predict the performance of the whole system of solar vehicle.

2. Modelling Photovoltaic Collection System

The Ánibal's solar collection system consists in three photovoltaic modules in series, a power regulator and two 12 volts batteries. The following table describes the parameters of the photovoltaic module in standard conditions:

Standard Conditions Module Parameters (ENECOM HF130)		
Parameters	**Descriptions**	**Values**
Isc (A)	Short circuit current	8.61
Voc (V)	Open circuit voltage	20.1
Pmax (W)	Maximum power Wp	130
NOCT (°C)	Nominal Operating Cell Temperature	47
Ns (Cells)	# cells in series	32
Np (Cells)	# cells in parallel	1
dV/dT (V)	Voltage variation with temperature	-0.08

Table 1

For the Cartagena Racetrack, it will be climatic data [3]:

Irradiation in the horizontal plane Cartagena Racetrack

Month	Hh	TD	HPS
Oct	3990	22.2	3.99
Year average	**5150**	**20.4**	**5.14**

Table 2

Hh: Irradiation in the horizontal plane (Wh/m2/day)
TD: Average Temperature Day (°C)
HPS: Solar peak hour, hour of sunlight equivalent per day (hr)

$$HPS = \frac{Hh(Wh/m^2)}{G_{CEM}(1kW/m^2)} \quad (1)$$

With the HPS, the irradiance maximum (Gmax) and its time can be calculated the range of time when there is useful sunlight. The table 3 shows that for a HPS in October of 5.38 hours and with a Gmax of 575 W/m2, it will have a range of time between 9:11AM and 2:33PM (the different point and irradiance data are in the Table 4). And the average of these irradiances data (Gm) is the representative irradiance for October.

Monthly average irradiance in Cartagena Racetrack					
Month	HSP (hrs)	Gmax (W/m2)	Hour Gmax	Time range	Gm (W/m2)
October	5.38	575	11:52	9:11AM-2:33PM	**521.8**

Table 3

For estimations of photovoltaic module performance in operative conditions, it will be used the next equations for its characterization [4]:

$$I_{SC,CO} = I_{SC} \times \frac{Gm}{G_{CEM}} = A \quad (2)$$

$$V_{OC,OP} = V_{OC,STD} + \left(T_C - T_{C,CEM}\right) * dVoc/dTc \quad (3)$$

$$T_C = T_a + C_2 * Gm = {}^oC \quad (4)$$

$$C_2 = \frac{TONC - {}_a}{G_{CEO}} = \frac{{}^oC * \imath^2}{W} \quad (5)$$

$$P_{max,CO} = FF * {}_{OC,CO} * {}_{SC,CO} \quad (6)$$

$$FF = \frac{P_{max,Mod}}{V_{OC,STD} * {}_{SC,STD}} \quad (7)$$

The power of the PV module (130 Wp) varies from 52 Wp as minimum to 70 Wp as maximum in operative conditions.

Characterization PV Module in Operating Conditions					
HPS October	G (W/m2)	Isc (A)	Voc (V)	Pmax (W)	Variation Vs. 130Wp(%)
09:22	417	3.59	19.29	52.02	-60.0%
09:37	445	3.83	19.22	55.32	-57.4%
09:52	471	4.06	19.16	58.35	-55.1%
10:07	493	4.24	19.10	60.91	-53.1%
10:22	514	4.43	19.05	63.33	-51.3%
10:37	531	4.57	19.01	65.28	-49.8%
10:52	546	4.70	18.97	66.99	-48.5%
11:07	557	4.80	18.94	68.24	-47.5%
11:22	566	4.87	18.92	69.26	-46.7%
11:37	572	4.92	18.91	69.94	-46.2%
11:52	575	4.95	18.90	70.28	-45.9%
12:07	575	4.95	18.90	70.28	-45.9%
12:22	572	4.92	18.91	69.94	-46.2%
12:37	566	4.87	18.92	69.26	-46.7%
12:52	557	4.80	18.94	68.24	-47.5%
13:07	546	4.70	18.97	66.99	-48.5%
13:22	531	4.57	19.01	65.28	-49.8%
13:37	514	4.43	19.05	63.33	-51.3%
13:52	493	4.24	19.10	60.91	-53.1%
14:07	471	4.06	19.16	58.35	-55.1%
14:22	445	3.83	19.22	55.32	-57.4%

Table 4

The figure 2 shows how can be estimated the solar energy available between ranges of time in Cartagena Racetrack for October. With the equation of the Irradiance/Time curve and doing a defined integration (Equation 8) with the time period that the solar car competes, it can be calculated.

$$Hh_{(\Delta T)} = \int_{T1}^{T2} \left(0X^4 - 0.066X^3 + 0.575X^2 + 36.53X + 21.06\right) dx \quad (8)$$

And with next equation, we can estimate the electric energy that the PV system can generate:

$$E_{FV} = \frac{PR \times Hh_{(\Delta T)} \times P_{max}}{G_{CEM}} = Wh \quad (9)$$

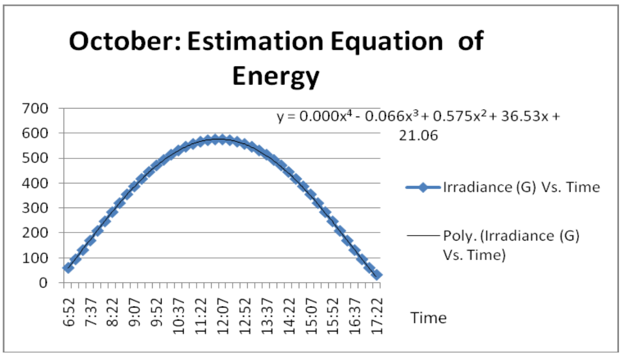

Fig. 2 Estimation of Energy

3. Kinematic and dynamic model of Ánibal solar vehicle

For the propulsion modelling of the Anibal vehicle we could be divided in two parts. In one part we have the electric part, and the other the mechanic part.

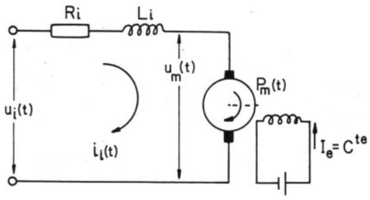

FIG 3

The electric modelling part is based on a DC motor with independent exciting. The Figure 3 shows the equivalent circuit of this motor, so the operation of electric part is given as [5]:

$$U_i(t) = \Delta \quad (10)$$

If the Ohm's law is applied:

$$U_i(t) = I_i R_i + \quad (11)$$

is given as [5]:

(12)

<u>All velocity terms that shows in the text should be expressed in function of the linear velocity</u> of the car however ω(t) is the angular velocity of the wheel. The next equations shows how change the angular velocity to linear velocity:

(13)

If the equation (12) and (13) is substituted in equation (11), finally we have the next expression for the linear velocity:

$$U_i(t) = I_i R_i + L_i \frac{dI_i(t)}{dt} + K_b \cdot \quad (14)$$

For finalize the electric part, the electric torque is defined as [5]:

$$T_m(t) = K_T \phi I_i(t) \quad (15)$$

And the magnetic flow is given as:

$$\phi = K_E I_e \quad (16)$$

If the equation (16) is substituted in equation (15), and we should remember that I_e is constant so the electric torque is given as:

$$T_m(t) = K_P I_i(t) \quad (17)$$

And now the mechanic part analysis will be developed. The Figure 4 shows the diagram of mechanical part.

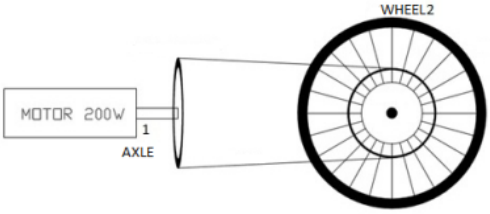

FIG. 4

We should take into account that subscript "1" makes reference of motor axle part, and the subscript "2" makes reference of wheel part. The torque and speed changes between part 1 and part 2 as given as:

$$\omega_1(t) = G(t)\omega_2(t) \quad (18)$$

$$T_2 = T_1 G(t) \quad (19)$$

This information will be utility in the following mathematical and physical definitions. So in our model the resistant torque is given as:

$$T_r(t) = K_1 \frac{dv_2(t)}{dt} + K_2 v_2(t) + K_3 f(\alpha) + K_4 \left(v_2(t)\right)^2 \quad (20)$$

This equation is composed of 4 terms. Where K1 is composed for 2 terms and represents the torque necessary for the acceleration of the car; the first term is given as [6]:

$$T_{r,ac\ motor}(t) = J \cdot \frac{d\omega_1(t)}{dt} = J \cdot \frac{G(t)}{r} \cdot \frac{dv_2(t)}{dt} \quad (21)$$

The equation 21 represents the torque necessary for acceleration of the axle of the motor.

The other term of K1 is given as:

$$T_{r,ac\ car}(t) = F_{ac\ car}(t) \cdot d \quad (22)$$

And the effort necessary for acceleration car is given as [7]:

$$F_{ac\ car}(t) = ma(t) = m \frac{dv_2(t)}{dt} \quad (23)$$

Substituting the equation (23) in equation (22):

$$T_{r,ac\,car}(t) = m\frac{dv_2(t)}{dt}\cdot d \quad (24)$$

Finally K1 is given as:

$$T_{ac}(t) = \left(J\cdot\frac{G(t)}{r}+\frac{m\cdot d}{G(t)}\right)\cdot\frac{dv_2(t)}{dt} \quad (25)$$

In the next expressions is developed the term K2.This term exists when the car has speed so this term represents the torque necessary for the speed. K2 is given as [6]:

$$T_{speed}(t) = B\cdot\omega_1(t) \quad (26)$$

If the equation (26) is changed in function of the linear speed it is given as:

$$T_{speed}(t) = B\cdot V_2(t)\cdot\frac{G(t)}{2\pi r}\cdot 60 \quad (27)$$

Now K3 will be explained as the term that represents the necessary torque for overcome the friction effort and the effort of weight. The Figure 5 shows these efforts.

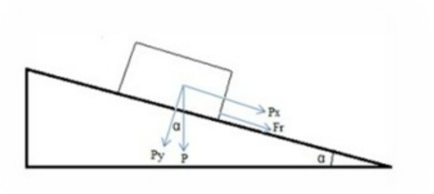

FIG. 5

$$T_{fw}(t) = (\mu mg\cos\alpha(t) + mg\sin\alpha(t))d \quad (28)$$

The equation (28) represents the torque in wheel, if this torque is change from wheel to the axle of the motor; it obtains the equation (29):

$$T'_{fw}(t) = (\mu mg\cos\alpha(t) + mg\sin\alpha(t))\frac{d}{G(t)} \quad (29)$$

Finally K4 represents the energy missed for aerodynamic friction. The torque of this energy missed is given as [8]:

$$T_{aero}(t) = \frac{1}{2}\rho AC_d(V_2(t))^2\, d \quad (30)$$

The equation (30) represents the torque in wheel, if this torque is change from wheel to the axle of the motor; it obtains the equation (22):

$$T'_{aero}(t) = \frac{1}{2}\rho AC_d(V_2(t))^2\,\frac{d}{G(t)} \quad (31)$$

This model has been implemented and simulated in Matlab and Simulink. The Figure 6 and 7 shows the principal screen of the program created. In the figure 6, the squares red and blue contains the modelling for the motor DC. And the green square in the figure 7, contains the equations for modelling all the terms (K1, K2, K3 and K4) that affects the vehicle for calculation of the velocity.

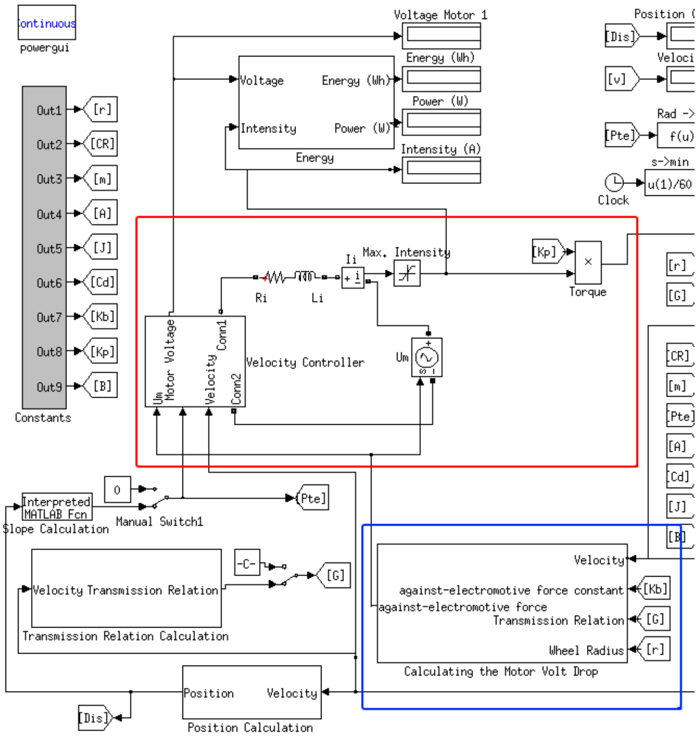

FIG. 6

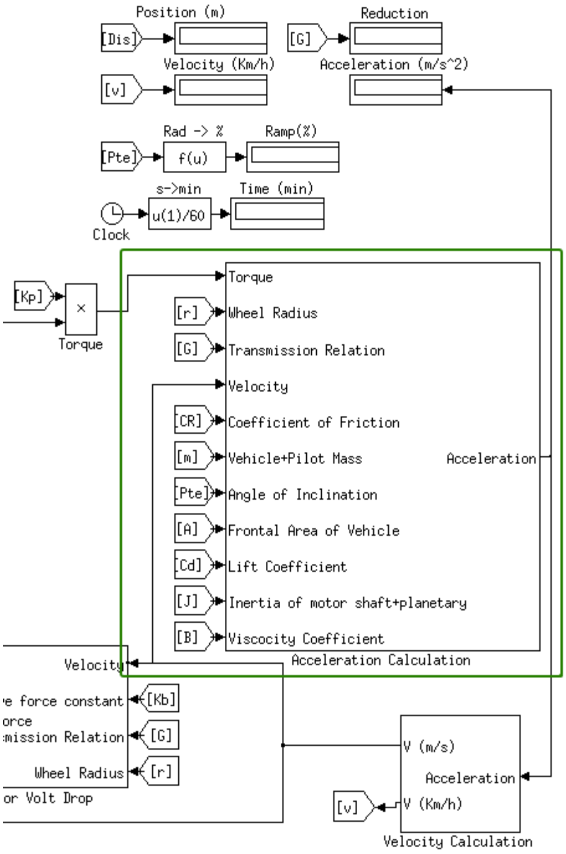

FIG. 7

The next figures are the result of the modeling simulation. The figure 8 represents the Voltage Vs. Time. And the figure 9 represents the Intensity Vs. Time.

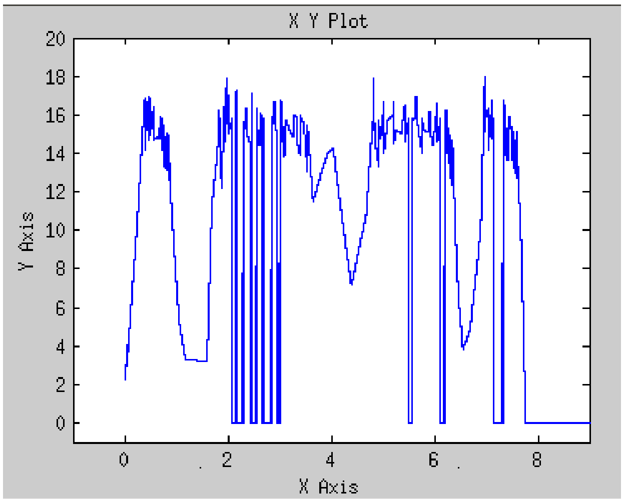

FIG. 8

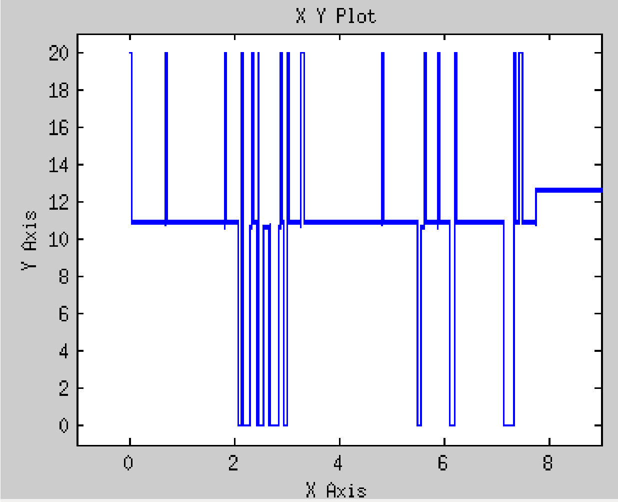

FIG. 9

Glossary:

-$U_i(t)$: drop voltage in induced (V)
- ΔV_R: drop voltage in resistance (V)
- ΔV_L: drop voltage in inductance (V)
- $U_m(t)$: drop voltage in motor (V)
- I_i: current in the induced (A)
- R_i: resistance of induced (Ω)
- L_i: inductance of induced (H)
- $\omega_1(t)$: angular speed in the axle (rpm)
-$n_1(t)$: angular speed in the axle (rad/s)
- $v_2(t)$: linear speed of the car (m/s)
- r: spoke of the wheel (m)
- G(t): transmission ratio.
- $T_m(t) = T_1(t)$: torque in the axle of motor
-φ: electromagnetic flow (Wb)
- K_F: constant (V/rpm)
- I_i: excitation current (A) (Constant)
- $\omega_2(t)$: angular speed in the wheel (rpm)
- $T_r(t)$: total resistance torque (Nm)
- α: angle of inclination (°)
- $T_{r,acmotor}(t)$: torque necessary of acceleration of the motor (Nm)
- J: rotor inertia (Kgm²)
- $n_2(t)$: angular speed in the wheel (rad/s)
- d: diameter of the wheel (m)
- $T_{r,accar}(t)$: torque necessary of acceleration of the car (Nm)
- $F_{accar}(t)$: effort necessary of acceleration of the car (N)
- m: total mass (Kg)
- a: acceleration of the car (m/s²)
- $T_{ac}(t)$: total torque necessary of acceleration (Nm)
- $T_{speed}(t)$: torque required for speed (Nm)
- B: constant of viscosity terms of the motor (Nm/rpm)
- $T_{fw}(t)$: torque necessary because of weight and friction effort in wheel (Nm)
- g: gravity (m/s²)
- μ: friction coefficient (No unit)
- $T'_{fw}(t)$: torque necessary because of weight and friction effort in axle of the motor. (Nm)
- $T_{aero}(t)$: torque necessary because of friction effort with air in wheel (Nm)
- $T'_{aero}(t)$: torque necessary because of friction effort with air in axle of the motor (Nm)
- A: frontal area (m²)
- ρ: air density (Kg/m³)
- Cd: lift coefficient (No unit)

4. Model Validation

To perform a more accurate analysis and get a real understanding of the behavior and performance of the solar car, acquire experimental data is needed.

For that purpose, a monitoring system has been developed. It composed by a series of sensors, and a real-time embedded controller. The sensors measures the electrical parameter of the vehicle (DC current and voltage of motor system, DC current and voltage from PV generator), and other variables like the speed and position. The embedded controller works like a data logger, which collects the sensor signals, makes a small processing in the progress then stores them, for later use.

This data allows us to confirm that the system behaves according to the design, besides allows us to make improvements and adjustments based on these experimental data, which results in a continuous improvement process.

Also, the acquired data allow us to test and improve the Solar Car mathematical model. A well-tuned model is an important tool to have reliable simulations. Through simulations we can develop the upgrades at low-cost and on a short time.

The real-time embedded controller is Compact RIO from National Instrument. Voltage values of battery bank and PV generator could be measured directly by the Compact RIO thanks to NI-9221, a module that can measure analog voltage up to 60V. Current values of the system were measured with Hall Effect sensors. The current sensors output were connected to a NI-9201, an 8-channel analog input module.

All data is extracted from Compact RIO by FTP connection. A Matlab script makes this connection, download the data files and process them. An automatic report is generated by the script, which is well-explained and can be interpreted by any member of the team.

In the next figure, measured data of voltage and current data are shown as a result of the monitoring system.

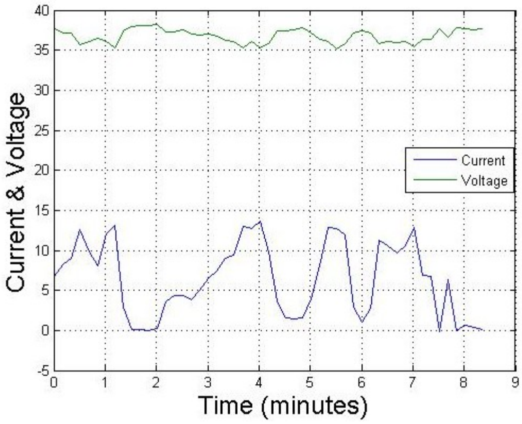

FIG. 10

5. Conclusion

The energetic modelling of a solar vehicle provides a general idea of what actually will be its functioning. It also provides information needed for sizing the drive system for the vehicle to move efficiently, and photovoltaic system uptake. Thus allowing knowledge of the energy that can be consumed and produced by location, month and length of time that the solar car driving.

Comparing the modelling result with the experimental result, we have different curves of voltage and intensity. Where the modelling curves represents the ideal behaviour for the vehicle in the track. With this reference we can make changes for the energy optimisation.

When there are situations where streets or roads have slopes, this energetic modelling is useful because we can estimate the energy consumption. Finally, energetic modelling can be used to program strategy for competitions such as the Murcia Solar Race, because we take in account not only considerations about the vehicle also race track considerations, and this is the differentiation with others vehicle simulator.

References

[1] R. J. King, “Photovoltaic applications for electric vehicles,” Photovoltaic Specialists Conference, 1990., Conference Record of the Twenty First IEEE, pp. 977–981 vol.2, 21.

[2] http://www.murciasolarrace.com/en/what-solar-race (Viewed: 25/10/2012).

[3] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php# (Viewed: 25/10/2012).

[4] E. Lorenzo, “Volumen II: Radiación Solar y Dispositivos Fotovoltaicos” (2006)

[5] Fraile, M. J., Maquinas eléctricas, 5ta Ed. (Mc Graw Hill, España, 2003).

[6] Álvarez, M.S., Modelo matemático de un motor de corriente continua separadamente excitado: Control de velocidad por corriente de armadura (2012 artículo)

[7] Newton, I. Philosophiae naturalis principia mathematica. (1687).

[8] http://es.wikipedia.org/wiki/Sustentaci%C3%B3n (Viewed: 12/08/2012).