

Modelling and Simulation of a Photovoltaic Solar System with Lead-Acid Battery

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Abstract

Nowadays technology bring us different tools to perform more complex and accurate simulations with the aim of developing new technology and tools, expending as less money as is possible and increasing the possibilities of applying HIL and SIL concepts in the industry, education, and research fields. In this work, a mathematical model representation is performed for a photovoltaic single cell and a lead-acid battery in charging and discharging mode, simulated in Matlab in order to observe the behavior and limits of each model, through Matlab, where the dynamics of both (photovoltaic cell and battery) are studied and simulated using the data acquire from the results of the cell and feeding back into the battery, where the battery is capable of being complete charged in 3 hours of continuous solar irradiation.

Keywords: Solar Energy; Photovoltaic Cells; Lead-Acid Battery; HIL; Matlab

INTRODUCTION

In the recent years the last technological advances have had possible to develop alternative ways to design systems each more complex and accurate through of different simulation tools like HIL and embedded platforms. That is the reason why mathematical models have started to acquire more importance and as can be seen in [1] and [2], where the authors define their own mathematical models of PV cells, batteries and converters, which are simulated on Matlab using Simulink obtaining results of their behavior similar to the real ones.

Similarly, in [3] the model of each component of the solar system is shown and described, then a simulation in Simulink and Matlab Code are performed testing different architectures of the internal behavior, finally the simulation was traduced into a physical system, testing out each component and behavior, where the main result was that Simulink simulation has less precision than the one done in Matlab Code, where results obtained are almost the same than the ones found in the real system.

In [4] a dynamic modeling of batteries are performed with the aim of replicating the behavior of them, due to their complexity and variability, where each battery behaves in different way, even the ones that are of the same class as seen in [5] and [6] where due to the physical and environmental conditions of the

batteries the models shown are an approximation of the real behavior of these.

On the other hand, in [7] a study of a portable solar energy lithium battery charger was designed, which was simulated using an algorithm in two steps, where resulted a physical system and a comparison between the results of the algorithm simulated in Matlab and the dynamic of the real model. In [8], one of the more complex studies where a photovoltaic system with maximum power control to supply a load with alternating current was designed and simulated step by step using Matlab and different software obtaining a complete operating system tested at different levels (starting in residential houses).

Now in [9] and [10] the mathematical models obtained from photovoltaic solar cell were used to establish its behavior by modifying environmental conditions like the ambient irradiation, the temperature, among others, even so, the effect of connecting these cells in different ways, all of this to determinate the best ways to use this technology in the most optimal way, and both studies were carried out without the need of a physical system.

Finally, in [11] and [12] another alternative to implement mathematical models of PV systems with an educational purpose is presented, where the mathematical model of the system dynamics are described and studied through a comparison between the obtained result and the real models, all of these with the aim of teaching how these systems work and are implemented, identifying the limits of these on how can be boosted to leverage as much energy as possible. That is the reason why in this paper a mathematical representation of a PV system is developed step by step, measuring the critical points of a real photovoltaic system in order to be implemented in a virtual laboratory.

METHODOLOGY

With the purpose of implementing a photovoltaic system for embedded architectures and software, it is necessary to develop a mathematical model for each one of the compounds approximating their real behavior, through of identifying the works conditions and the maximum and minimum values that the whole system can deliver. The circuit scheme of the photovoltaic cell is shown in Figure 1.

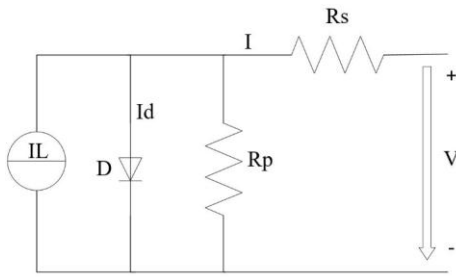


Figure 1. Photovoltaic Cell Electrical Representation

A. Photovoltaic Cell

Initially, the first model to study is a single solar photovoltaic cell, due to a cause of its nature is the one with the greater mathematical development. Then, the characteristic equation as is described in [13] and [14] is shown in 1.

$$I = I_{ph} - I_d - I_p \quad (1)$$

Where I_{ph} is the photovoltaic current, I_p is a parasitic current caused by the equivalent parallel resistance identified R_p and I_d is the diode current, which is inversely proportional to the saturation current and is defined in equation 2.

$$I_d = I_o \left[e^{\frac{V+IR_s}{AN_sV_T}} - 1 \right] \quad (2)$$

From equation 2 I_o is defined as the leakage current of the diode, V is the diode voltage, R_s is the equivalent series resistor, A is the ideality factor which depends on the cell technology, N_s is the number of photovoltaic cells connected in series, and V_T is the thermal voltage defined in equation 3.

$$V_T = \frac{KT_c}{q} \quad (3)$$

Then, K is the Boltzmann constant which is $1.380e-23$ J/K, q is the electron charge $1.602e-19$ C, and T_c is the actual cell temperature measured in Kelvin. Replacing equation 2 in 1 and defining I_p the total current of the cell is shown in the equation 4.

$$I = I_{ph} - I_o \left[e^{\frac{V+IR_s}{AN_sV_T}} - 1 \right] - \frac{V + R_s I}{R_p} \quad (4)$$

To determinate the values of I_{ph} and I_o , the equations 5 and 6 are applied.

$$I_{ph} = \frac{(I_{ph,ref} + \mu\Delta T) * G}{G_n} \quad (5)$$

$$I_o = I_{sc,ref} \left(\frac{T_c}{T_{c,ref}} \right)^3 e^{\frac{-V_{oc,ref}}{AN_sV_T}} e^{\left[\frac{qEG}{AK} \left(\frac{1}{T_{c,ref}} - \frac{1}{T_c} \right) \right]} \quad (6)$$

Where $I_{sc,ref}$ is the nominal current saturation of the Diode which can be determined by equation 7, G is the actual

irradiance, G_n is the nominal irradiance estimated in 1000 W/m^2 , ΔT is the difference between the actual temperature value T_c and the reference value $T_{c,ref}$ defined as $298 \text{ }^\circ\text{K}$ and μ is the current temperature coefficient granted by the datasheet.

$$I_{sc,ref} = \frac{I_{ph} - \frac{V_{ocn}}{R_p}}{e^{(N_s * V_{ocn} / V_t * A)} - 1} \quad (7)$$

Now, in order to calculate the value of R_s and R_p it is necessary to find the point where both satisfy that the maximum experimental power would be the same that the maximum theoretical power or in other words $P_{max,m} = P_{max,e} = V_{mp} I_{mp}$ as is described in [15] and [16]. Therefore, the method this work is going to apply requires to determinate the value of $R_{s,max}$ and $R_{p,min}$ which both can be found using equations 8 and 9.

$$R_{s,max} = \frac{V_{oc} - V_{mp}}{I_{mp}} \quad (8)$$

$$R_{p,min} = \frac{V_{mp}}{I_{sc,n} - I_{mp}} - R_{s,max} \quad (9)$$

To determinate the actual short circuit current (I_{sc}) and the nominal light-generated current ($I_{ph,ref}$) the equations 10 and 11 must be used.

$$I_{ph,ref} = \frac{R_s + R_p}{R_p} * I_{sc,n} \quad (10)$$

$$I_{sc} = \frac{(I_{sc,n} + \mu\Delta T) * G}{G_n} \quad (11)$$

The value of $I_{sc,n}$ is granted by the datasheet of the photovoltaic solar cell, R_p is calculated by equation 12 and R_s starts from 0 and is tested each 0.001 of increase with R_p until the condition given above is accomplished as is described in [17] and [18].

$$R_p = \frac{V_{mp}(V_{mp} + I_{mp}R_s)}{V_{mp}I_{ph} - V_{mp}I_{sc,ref} * e^{\frac{V_{mp} + I_{mp}R_s}{AN_sV_T}} + V_{mp}I_{sc,ref} - P_{max,e}} \quad (12)$$

Once the values of R_s and R_p are calculated, the mathematical model of the photovoltaic cell is determined by equation 1 which vary depending proportionally by the irradiance and inverse proportionally by the temperature.

B. Lead-Acid Battery

Basically, the lead-acid battery model is determined by equation 13, which depending on the state of function vary between + or -, the first one is for the charging state and the second one is for the discharging state as is described in [19].

$$V = E_m \pm IR \quad (13)$$

From this single representation model V is the current voltage of the battery, E_m is the open circuit voltage defined in the equation 14 as is described in [6], I is the actual current used by an external charge (which in idle state is approximated to 0) and R is the internal resistance, which vary depending on different parameters such as capacity, charge/discharge current, temperature, among others.

$$E_m = E_{m0} - K_e(273 + T_e)(1 - SOC) \quad (14)$$

From equation 14, E_{m0} is the open circuit voltage at maximum charge, K_e is a constant granted by datasheet, T_e is the electrolyte temperature and SOC is the state of charge, which can be found applying equation 15.

$$SOC = \frac{q - q_{dis}}{q_{max}} \quad (15)$$

Where q is the actual battery charge calculated by the result of $I * t$, q_{dis} is the actual battery discharge rate and q_{max} is the battery capacity. Due to the variable value of the internal resistance, many models have been proposed based on the experimental identification of the battery parameters, that's the reason why in this studied a battery model developed by CIEMAT which has the ability to cope a wider range of lead-acid batteries as is described in [20]. The model for charging and discharging state are shown in equation 16 and 17 respectively.

$$V = [2.085 - 0.12(1 - SOC)] - \frac{I}{C_{10}} \left(\frac{4}{1 + I^{1.3}} + \frac{0.27}{SOC^{1.5}} + 0.02 \right) * (1 - 0.007\Delta T) \quad (16)$$

$$V = [2 - 0.16SOC] + \frac{I}{C_{10}} \left(\frac{6}{1 + I^{0.86}} + \frac{0.48}{(1 - SOC)^{1.2}} + 0.036 \right) * (1 - 0.025\Delta T) \quad (17)$$

From both equations, the section enclosed between square brackets represents the open circuit voltage EMF variation with the state of charge and the second one represents the sum of series resistances caused by different phenomenons inside the battery, which combined are the internal resistance of the battery. Additionally, C_{10} is the battery capacity rating when the battery is complete discharged over 10 hours and the value is granted in the datasheet, and finally ΔT is the temperature variation between the temperature reference (25°C) and the internal battery temperature.

RESULTS

Initially in Matlab was developed the algorithm to calculate R_s and R_p , by simulating an existing solar cell which parameters were obtained from [21], then the values of both resistances are:

$$R_s = 0.276 \Omega$$

$$R_p = 1136.56 \Omega$$

Therefore, the photovoltaic solar cell behaviour was simulated with the aim of establish the maximum operating points of current, voltage and power and the results are shown in figure 2.

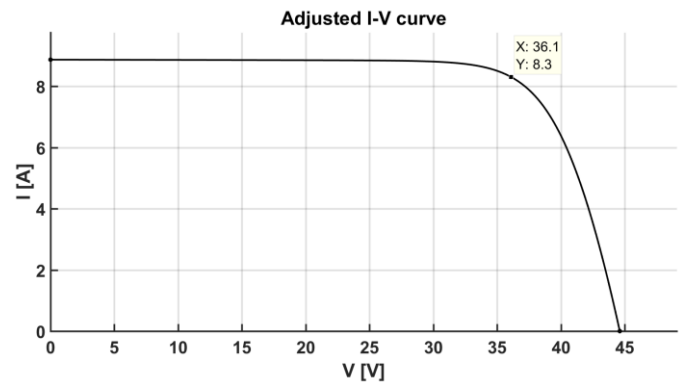


Figure 2. I-V Curve of the photovoltaic Cell Model

The I-V curve is shown in figure 2 with the maximum operating point at 8.3 A with 36.1 V, Now the P-V curve is shown in figure 3.

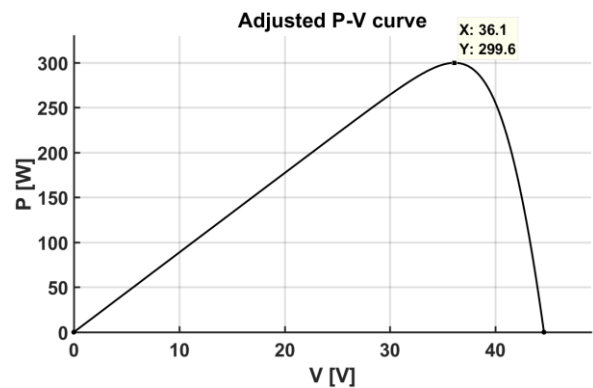


Figure 3. P-V Curve of the photovoltaic Cell Model

The P-V curve is shown in figure 3 with the maximum operating point at 300 Watts with 36.1 V. Now the lead-acid battery model is implemented using the data obtained from the photovoltaic cell model, where the capacity of charge is the 8.3 Amperes per second, for the battery model was used the manufactured data of [22], the results of the discharging mode applying a constant load of 25 Amperes over 3 hours is shown in figure 4.

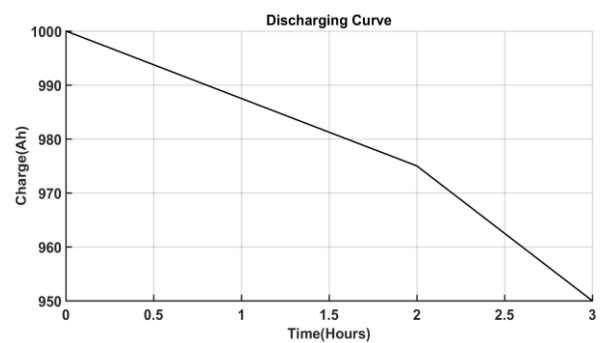


Figure 4. Discharging Model of the Lead-Acid Battery

From figure 5 the discharging model shows a constant discharge where the capacity of the current is decreasing according across the time where the load is consuming energy without charging the battery for 3 hours. Figure 6 shows the voltage performance during this period.

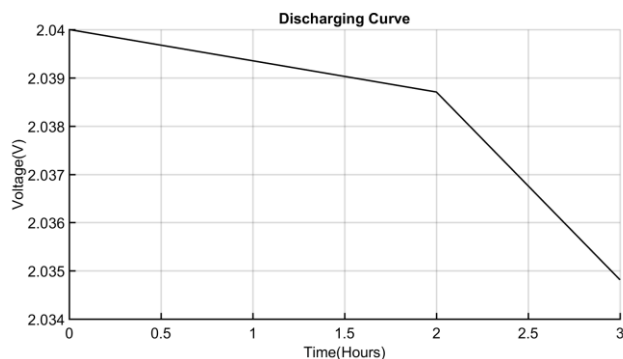


Figure 5. Voltage discharge behaviour of the Lead-Acid Battery

Now for charging the battery using the data of the photovoltaic solar cell, the resulted charging curve is shown in figure 6.

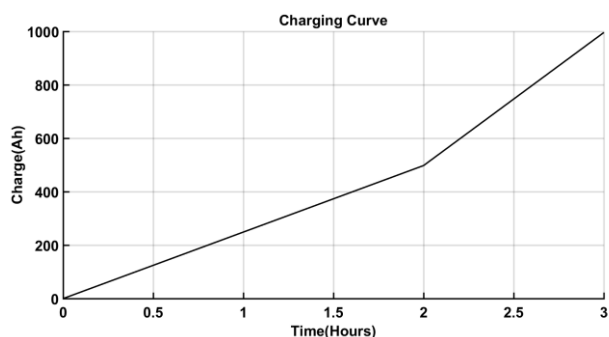


Figure 6. Charging Model of the Lead-Acid Battery

The complete charge of the battery, which is a lead-acid battery of 2V at 1000Ah is reached in 3 hours using the extracted current from the photovoltaic cells module. Additionally, the voltage behaviour is shown in figure 7.

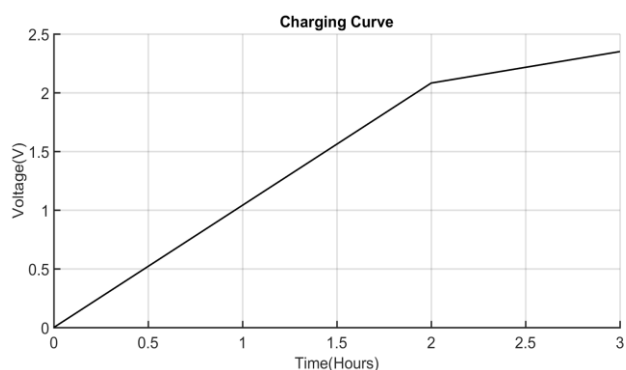


Figure 7. Voltage Charge behaviour of the Lead-Acid Battery

CONCLUSIONS

Initially, the use of mathematical models as a way of emulating systems can be appreciated, showing the capacity of the modules, the operating points and the operation of the whole compounds combined, where without using physical structures in this case it was possible to determine the time or charging and discharging the battery using a module of 72 single solar cells.

After testing the algorithm and equations (16 and 17) proposed by several articles, the resulted dynamics is according with the one showed by the datasheet, which is tested under a real lead-acid battery. Additionally, the charging time using a single solar cell is about 3 hours of solar irradiation, allowing to harvest even more energy or even so introducing it into the network.

According to the results obtained from Matlab, the resulted mathematical models can be applied in different fields like virtual laboratories, where through different simulation tools, these models can offer a complete understanding of the complete photovoltaic system behavior and the benefits that this technology can bring.

ACKNOWLEDGMENT

The authors express their gratitude to the Vicechancellorship of investigations of the Military University Nueva Granada, for the financing of the project INV-ING 2370 in 2017.

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