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MODELING THE I- λ -T CHARACTERISTIC FOR PHOTOVOLTAIC SYSTEMS STORAGE BATTERIES DURING CHARGING PROCESS

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Abstract. ***In this paper is presented a numerical method for measurement and analysis of the charging characteristics I-λ-t (battery current-irradiance-time) of storage batteries for photovoltaic (PV) power systems. The experimental data is obtained from the PV modules by a data acquisition system built in the charger component. An algorithm developed as a Matlab source code is used to model the charging characteristics of the batteries connected to a PV system. Using the interpolation method, the mathematical function of total battery current and depending on time and illumination are obtained. The numerical values of the errors between the theoretical and experimental results prove the accuracy of the proposed method.***

Keywords: PV systems, battery storage, charging characteristics, interpolation method

1. INTRODUCTION

Solar energy is considered to be one of the most important renewable energy sources of the present and future because it is infinite, clean and easy to use in any place on earth. For this reasons the photovoltaic (PV) systems that convert solar energy directly into electricity based on the photovoltaic effect have seen a rapid development in the past 20 years. Also the use of large PV systems can contribute to the achievement of energetic independence of a region or country and can provide electrical energy supply to remote areas [1], [2].

On the other hand, the PV systems have the big disadvantage of not producing constant. When the solar energy does not have an adequate level - during night, due to weather conditions such as clouds, blizzards, and e.a. – then the PV systems do not generate electricity. Thus, in order to improve the functionality of PV systems, energy storage systems had to be introduced. Today, the most used energy storage systems are electrochemical (battery, fuel cells, flow batteries) and electromagnetic (capacitors, ultra-capacitors, superconducting magnetic). This paper will analyse only the behaviour of batteries used to store energy during their charging process (while the sunlight is available). The conversion of the energy stored in the chemical bonds of the material into electrical energy through a set of electrochemical reactions is provided by a battery. The main criteria by which to choose batteries used in PV systems are: charging/discharging cycles, battery capacity and voltage, lifetime, maintenance requirements, and of course, efficiency. The manner in which it responds to the numerous and rapid charging-discharging cycles is the most critical characteristic of the battery used for PV system [3], [4], [5].

Based on monitored system parameters of grid connected 77 kWp PV system installed at Electrotechnical Research Institute in Bucharest, Romania (ICPE Bucuresti), this paper is proposing a numerical method to model the charging characteristics of the electrical energy storage system. During the charging process of storage batteries from PV system, the total battery current parameter is monitored. This battery characteristic is determined by the parameter variation in time and irradiation. A refinement algorithm of measured data and the interpolation method are used in order to obtain the approximate mathematical function of the battery characteristics. The errors achieved through the numerical algorithm prove the accuracy of the proposed method.

2. DATA ACQUISITION SYSTEM

The measurements are obtained with a specific data acquisition and control system built in the charger, as shown in Figure 1. The system consists of:

1) PV system - is composed of nine modules 230W TSM-230PC05 Solar Panel from Trina Solar, a set of three parallel modules connected in series, as shown in Figure 2;

2) The PV system is plugged to a charger Sunny Island SIC-MPT model that measures and controls the charging/discharging processes of storage batteries;

3) A group of sixteen BSB Solar 12V250AH lead-acid batteries consists of a set of four parallel batteries connected in series, and is linked to an inverter;

4) The inverter - Sunny Island SI 5048 model - converts the 48V DC into 230V AC needed to supply the consumer – an air conditioning system. The PV system and storage battery group are designed to offer total power supply independence for an air conditioning system used to cool down or heat a room of about 100 m^2 [6], [7], [8].

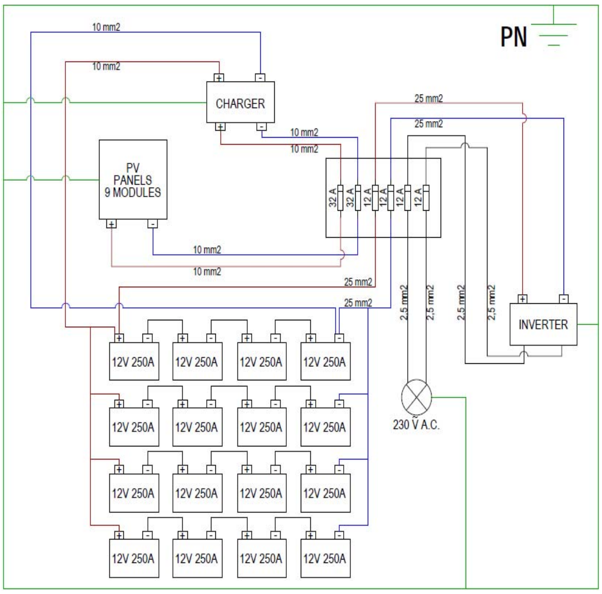

Figure 1. Data acquisition system.

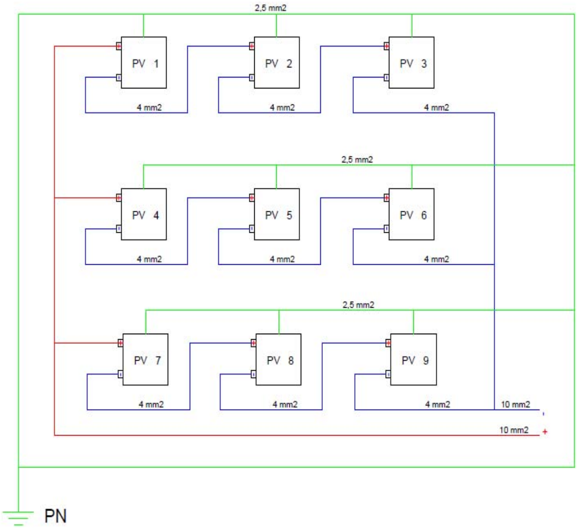

Figure 2. Connection scheme of the PV modules.

The charger performs several functions: controls the charging/discharging processes of the batteries, allows a discharge threshold of maximum 30% of the battery capacity, and it is also provided with the possibility to acquire measured data through a LAN port. Thus, all the charging parameters that were measured are provided by the charger. The parameters monitored by the data acquisition board during the charging process that were of interest to this paper are:

- - Total battery current (*TotBatCur*) - in A - represents the charge current provided by the charger to the battery.
- - Irradiance (*IntSolIrr*) - in W/m^2 - represents the level of sunlight (irradiance) that the PV modules are exposed to during the charge process. This parameter varies during the day and has a constant zero value during the night.
- - Time (*TimeStamp*) - in day/hour/minutes - indicates the values of the above parameters at any given moment of the day or night during charging process of the storage batteries. The data acquisition board embedded in the charger takes a sample at every 15 minutes.

All the data acquired from the charger is collected in a *.csv file then converted into a *.xls file in order to be easily imported into Matlab 2012a [9], [10], [11]. The function that is selected to be modeled is *f*(*TotBatCur, IntSollrr, TimeStamp*). The following symbols are used to describe the three parameters: *t* for *TimeStamp*, λ for *IntSollrr*, and *I* for *TotBatCur*. Using the collected data, the measured charging characteristics of the storage battery group are drawn by a Matlab algorithm.

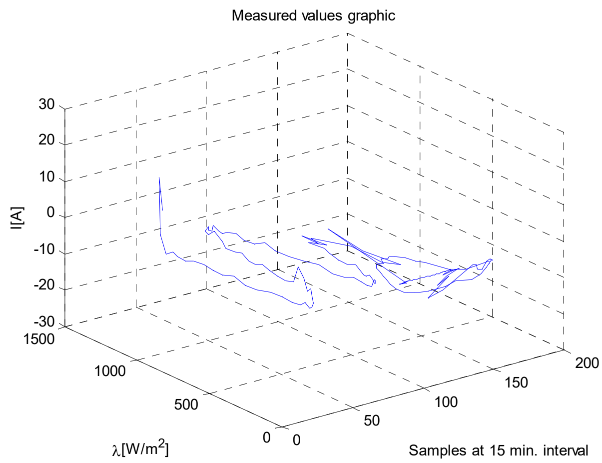

Figure 3. Measured characteristic *f*(*I, λ, t*).

3. NUMERICAL METHOD FOR MODELING THE BATTERY CHARGING CHARACTERISTICS

3.1 Experimental results

The Matlab function *plot3*(*x,y,z*) - used in *Matlab Procedure 1* shown in Figure 4 - is used to obtain the 3-D experimental (measured) characteristics through a set of measured data. In this method the function *plot3*(*I, λ, t*) is implemented representing the 3-D dependence of *I* on time and solar irradiance. The data acquisition process started when the 16-pack battery was discharged to the minimum level 33.07% permitted by the charger. Then, a slow charging process started, that stretched throughout seven days. From the measured data performed during the nights it is observed that parameter $\lambda = 0$, and thus the state of charge of the battery pack and battery charge voltage had remained at constant values obtained during the day. For these reasons the measured charging characteristic $f_m(I, \lambda, t)$, shown in Figure 3 dropped out from *.xslx file the measured data during all the nights throughout the complete slow charging process. In this way, in order to refine the initial measured data, the module *Matlab Procedure 1* uses the data from module *Refined Data Procedure 1* as presented in Figure 4. The numerical procedure for modelling the battery charging characteristic shown in Figure 4 is organized into several interconnected computational modules.

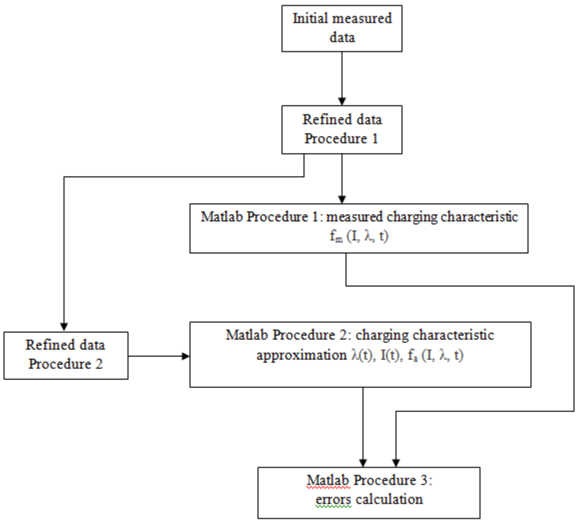

Figure 4. Numerical procedure

3.2 Interpolation method

In order to obtain the approximate mathematical function of the battery charging characteristics the interpolation method is used. Thus Matlab's ***"fit"*** function (the module *Matlab procedure 1 and 2*) find the optimal coefficients of the function approximation of characteristics $\lambda(t)$ and $I(t)$, as a sum of sinuses, using data obtained from the module *Refined data Procedure 1*. The approximation characteristics of $\lambda(t)$, and $I(t)$ are shown in Figure 5 and 6 and the interpolation functions are presented in relations (1) and (2).

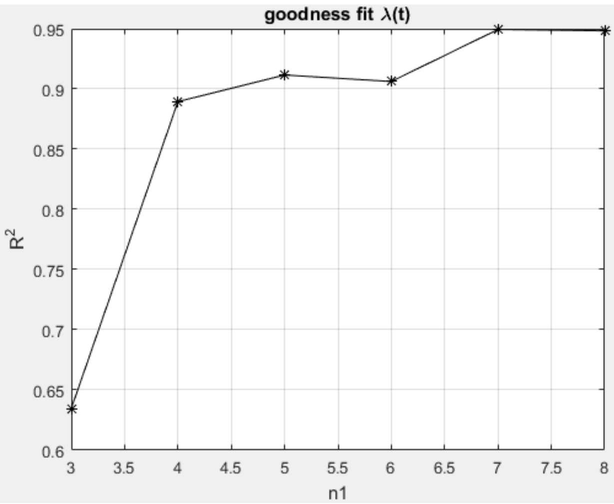

Figure 5. Characteristic approximation of $\lambda(t)$

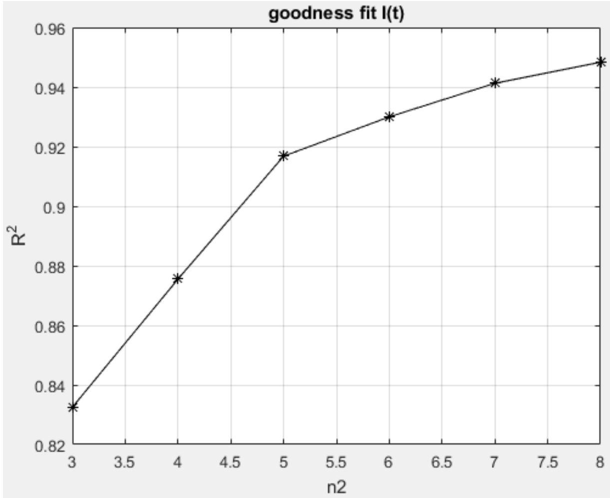

Figure 6. Characteristic approximation of $I(t)$

To determine the accuracy of the first interpolation procedure, the module *Matlab procedure 3 errors calculation* is used to calculate: the goodness of fit (SSE), the mean square error (MSE) and the root mean square error (RMSE). In Table 1 are shown the number (n) of terms of the approximation function and the numerical values or SSE, MSE, RMSE. Also, in Table 2, the coefficients for the two functions, $\lambda(t)$ and $I(t)$, are shown.

Table 1. Errors of interpolation method

	Refined data Procedure 1				Refined data Procedure 2			
	n	**SSE**	**MSE**	**RMSE**	**n**	**SSE**	**MSE**	**RMSE**
λ(t)	7	0,95	8632,26	92,91	6	0,96	5427,26	73,67
I(t)	8	0,95	4,2436	2,06	8	0,96	3,9601	1,99

$$\lambda(t) = \sum_{i=1}^{7} a_i * \sin(b_i * t + c_i) \quad (1)$$

$$I(t) = \sum_{i=1}^{8} a_i * \sin(b_i * t + c_i) \quad (2)$$

Table 2. Coefficients for characteristics $\lambda(t)$ and $I(t)$

λ(t) coefficients		*I(t) coefficients*	
a1	66,1	a1	30,74
b1	1,39	b1	3,062
c1	1,401	c1	0,7298
a2	857,7	a2	2,064
b2	2,294	b2	7,346
c2	-2,008	c2	1,971
a3	4,646e+04	a3	28,62
b3	8,786	b3	3,247
c3	2,446	c3	-2,418
a4	4,631e+04	a4	6,52
b4	8,795	b4	9,072
c4	-0,6992	c4	-1,466
a5	334,1	a5	6,343
b5	3,285	b5	9,632
c5	1,271	c5	1,829
a6	159	a6	239,7
b6	7,856	b6	0,02809
c6	-0,1956	c6	-3,141
a7	97,68	a7	2729
b7	13,35	b7	14,01

c7	0,7259	c7	-0,7894
a8		a8	2730
b8		b8	14,01
c8		c8	2,353

Also, based on interpolation functions (1) and (2) the 3-D approximation characteristics $f_m(I, \lambda, t)$ are obtained. In Figure 7 are shown and can be compared the two types of characteristics: measured and approximation (calculated).

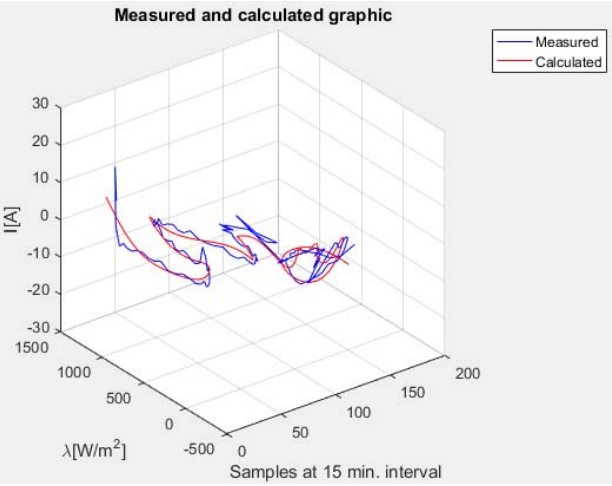

Figure 7. The approximation and measured characteristics $f_m(I,\lambda,t)$

Taking to consideration the small variations of the measured parameters *TotBatCur, IntSollrr* and the batteries state of charge over one hour and the insignificant variations of the battery charge voltage during an hour, a second *Refined data Procedure 2* to refine the measured data is created. This procedure uses data from *Refined data Procedure 1* and determines the average value over one hour for each measured parameter. The average value is computed as the parameter values sum of one hour divided by 4. Using these refined data as input for the *Matlab procedure 2* module it obtains the approximation characteristics $\lambda(t)$ and $I(t)$ and generates the interpolation functions given by relations (3) and (4). After that, the *Matlab procedure 3 errors calculation* module determines the accuracy of this second interpolation procedure. In Table 1 are shown the numerical values or SSE, MSE, RMSE, and the number of terms (n) of interpolation functions for this second case. Also for this case, the approximation characteristics of $\lambda(t)$ and $I(t)$ are shown in Figure 8 and 9.

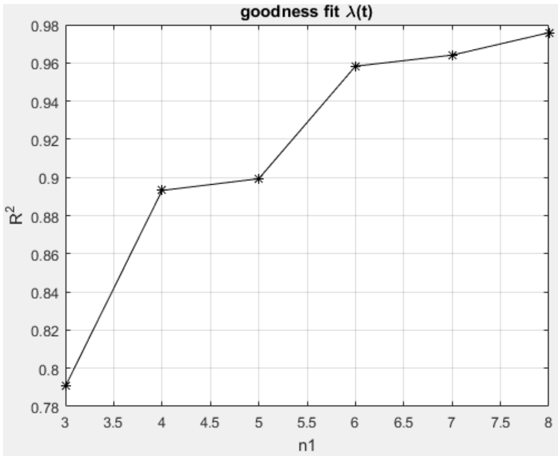

Figure 8. Characteristic approximation of $\lambda(t)$

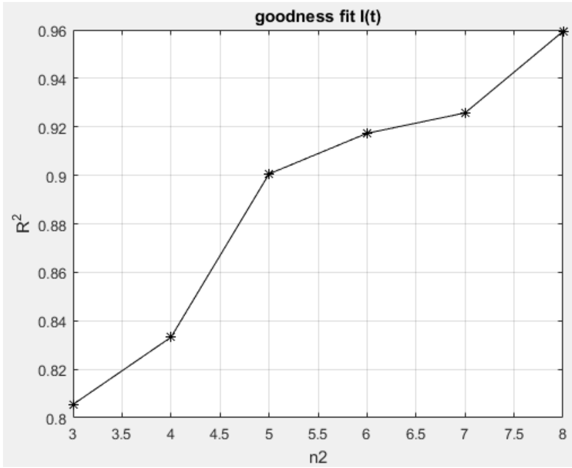

Figure 9. Characteristic approximation of $I(t)$

$$\lambda(t) = \sum_{i=1}^{6} a_i * \sin(b_i * t + c_i) \qquad (1)$$

$$I(t) = \sum_{i=1}^{8} a_i * \sin(b_i * t + c_i) \qquad (2)$$

Table 3. Coefficients for characteristics $\lambda(t)$ and $I(t)$

λ(t) coefficients		*I(t) coefficients*	
a1	861,6	a1	4507
b1	0,9737	b1	2,65
c1	2,235	c1	0,6213
a2	4300	a2	4459
b2	1,925	b2	2,655
c2	-0,6182	c2	-2,519
a3	1,181e+04	a3	51,71
b3	6,936	b3	2,112
c3	2,755	c3	-2,714
a4	1,17e+04	a4	31,55
b4	6,911	b4	9,918
c4	-0,3781	c4	1,862
a5	3860	a5	31,44
b5	2,032	b5	9,824
c5	2,613	c5	-1,317
a6	123,6	a6	1,336
b6	10,59	b6	13,17
c6	-1,935	c6	-0,5672
a7		a7	1,484
b7		b7	15
c7		c7	-2,852
a8		a8	0,9968

b8		b8	21,63
c8		c8	2,624

In Table 3, the coefficients for the two functions, $\lambda(t)$ and $I(t)$, obtained in this second case, are shown. Also, based on new interpolation functions (3) and (4) the 3-D average approximation characteristic $f_a(I, \lambda, t)$ is obtained. In Figure 10 is shown and can be compared the two types of characteristics: measured and average approximation (calculated). Analysing the errors values from Table 1 and comparing the characteristics from Figure 7 and 10 results in a better accuracy of the chosen interpolation method that uses the both refining modules: *Refined data Procedure 1* and *2*.

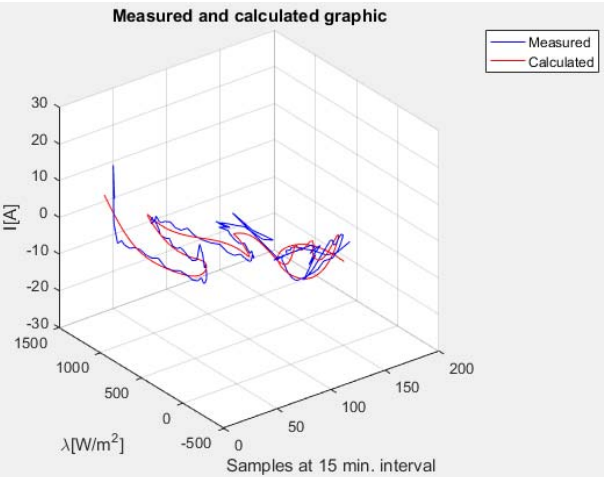

Figure 10. The calculated and measured characteristics of $f_a(I,\lambda,t)$.

4. CONCLUSIONS

In this paper was evaluated the charging process of a PV system's 16-pack lead-acid battery storage system. The whole group of batteries was modeled as a single battery, used to store energy generated by the PV system and to supply energy to the consumer during the less efficient periods of the PV panels.

A numerical procedure was created in Matlab in order to refine the data, and to analyse the measured and approximated characteristics of the charging process. The interpolation method helps to obtain the interpolation functions which can be used to model the 3-D approximation characteristics of charging parameters process with small errors. The accuracy of the approximation characteristics increases as the initial measured data is refined a couple of times (*Refined data Procedure 1* and *2*).

The proposed interpolation functions model the monitored charging parameters at any point during the charging process. The developed method can be extended for modeling charging process from PV system of all the battery types and facilitate the study of charging process parameters.

Another important characteristic that will be analysed in a different paper is the strong dependency between the state of charge of the battery (or group of batteries), irradiance and time. This will result in an accurate mathematical model that can predict with small error the charge level of the system related to the sunlight intensity and, of course, time.

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