FUZZY CONTROLLER APPLICATIONS IN STAND-ALONE PHOTOVOLTAIC SYSTEMS

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Abstract

One of foremost problems in stand-alone photovoltaic systems consists on the election of a strategy for charge controllers. The charge controllers main function is the accumulation system protection, and this leads to an extension of the batteries lifetime, thus reducing, the long term economic cost of the installation. This document describes a Fuzzy Logic based charge controller. In order to show the designed charge controller operation, firstly, a succession of simulations have been carried out to try out the mentioned controller efficiency. Afterwards, the designed charge controller has been used on a real target system to control the charge and discharge processes of a battery in a real stand-alone photovoltaic system, that is installed, on the flat roof of the E.P.S. Jaén of the University of Jaén (Spain). Finally, comparative operation results of the fuzzy charge controller developed are exposed in this document.

Keywords: Fuzzy Logic Controllers, Rules Based Systems, Charge Controller, Stand-alone PV-Systems.

1 INTRODUCTION

The operation of the stand-alone photovoltaic systems depends not only on the individual quality of the elements that compose them, but also of the interaction between the same within system [1]. In this sense, the charge controller achieves an outstanding role. The charge controller functionality is focused mainly in the accumulation system protection (constituted by Lead-Acid batteries). In spite of the continuous evolution in the charge control strategies for the batteries, supported by the operation of the charge controller; in practical implementation, at present time, its output have a relative high error rate.

However, there are many studies accomplished on the operation of batteries [2]. In these studies, we can notice the existence of an expert knowledge, which can be formalized as control rules in a Fuzzy control system [3].

These controllers are expert systems [3] that incorporate human knowledge in their knowledge bases through fuzzy control rules and fuzzy membership function [3][4]. A Fuzzy controller is composed by a knowledge base, which incorporates the information given by the operator of the controlled process following some linguistic control rules pattern.

In this document, the accomplished works carried out in order to implement a Fuzzy charge controller are described. We have to emphasize that though the current implementation, a high cost equipment such as a computer and an data acquisition system, is mainly used to analyse the behaviour of the controller. Future implementations will lack these elements, and therefore the designed device will carry out the present implemented functions.

This work is structured on the following manner: In section 2, a short introduction to stand-alone photovoltaic systems will be accomplished, which will be focused on a study of the usual operation of the charge controllers that exist at present time. Section 3 will be devoted to the justification of using a Fuzzy control system for the charge controller, listing some desirable operation characteristics for a charge controller. In section 4, the description of a Fuzzy charge controller, simulated on a computer, will be established; the operation results will be showed in section 5.

To test the supposed improvement of a fuzzy charge controller as compared to traditional charge controllers, two stand-alone photovoltaic systems have been considered; the first one uses a traditional charge controller and the second one incorporating a Fuzzy charge controller. The characteristics for each installation are described in section 6. Meanwhile, the description of the Fuzzy charge controller that it has been designed in the second installation is shown in section 7. In section 8, some of the operation results are exposed. Finally, section 9 is devoted to conclusions.

2 STAND-ALONE PHOTOVOLTAIC SYSTEMS. CHARGE CONTROLLER

Photovoltaic solar energy is, actually and in a small scale, a reliable and clean form of electrical energy production. The fundamental reason, which has prevented the expansion this technology has been basically economic: a greater cost of solar produced kWh than its respective production using more conventional technologies (oil, nuclear, coal, etc).

Nevertheless, the growth of technology and the production of cheaper modules, the development of more advanced conditioning systems of power, the greater efficiency and reliability, etc., in association with the accomplishment of research projects, supported by national and international programs of financing and/or partial subsidy, allows to install increasingly effective and competitive systems with conventional generators of electrical energy. So, it is expected an increasingly use of this technology in the production of electrical energy in the world as a complement of conventional generation sources.

There are different types of photovoltaic installations: The grid-connected photovoltaic systems (GCFS) are installation, which are designed in order to inject energy into the electrical net, either to sale the electrical production of our photovoltaic system, or to support the electrical net. In some occasions, the designated Stand-alone Photovoltaic Systems (SAFS)[7] are used, as for example in isolated places, in which supply is not easy through the electrical net. Approximately, 90% of the installed world power has been installed in SAFS [12]. A Stand-Alone Photovoltaic Systems, as shown in figure 2.1, is constituted by the following elements:

Photovoltaic Generator: Produces electrical energy from the incident solar radiation.

System of energy accumulation: Batteries inserted in the Stand-Alone Photovoltaic Systems are implemented in order to match different rates of production and demand of electrical energy.

Charge Controller: Its function consists on protecting the system of accumulation and avoiding extreme behaviour cases that could injure the batteries.

Inverter: It is used when we want to manage loads that require alternate current.

Load: Elements fed with electrical energy.

2.1 Charge Controllers

The generated electrical energy not only feeds the electrical load, but also, due to the surplus of generated energy, loads the accumulators. Therefore, the regulator system must avoid overcharges in the accumulator (because of an excessive voltage provided by the generator), and, on the other hand, prevent the overdischarging of the batteries (in case of an excessive feed to the load by the accumulation system).

In fact, the charge controller system must protect to the accumulator of extreme operation situations, independently of the size of the installation, of its design, and possible weather variations in consumption profiles, solar radiation and operation temperatures. All this, in order to achieve as final objective a longer useful life of the accumulation system.

It exists different kinds of charge controllers [7], but the most frequently used in Stand-Alone Photovoltaic Systems is the two-switched serial controller (Generation and Consumption). In this serial controller, the generator switch disconnects the generator and the battery when the latter reaches to a value enough to overcharge itself. The consumption switch energy prevents to supply the voltage of the battery when it reaches to a minimal threshold. The characteristic values in this type of controller are the following [10]:

Overcharging threshold voltage V_{SC}: Maximum voltage that the regulator allows to reach the battery. If V>VSC then the battery is disconnected of the generator.

Charge rearming Voltage V_{RC}: It is the value of the battery voltage that enables the battery to the generator reconnection. In the figure 2.2 the overdischarging Histeresis cycle corresponding is presented.

Overdischarge voltage threshold V_{SD}: It is the minimal value allowed for the battery voltage before disconnecting it from the consumption. If V<VSD then the battery will be unplugged from the consumption.

Rearming voltage for discharge V_{RD}: It is the voltage value in the battery that causes the battery reconnection to consumption. In the figure 2.3 overdischarging Histeresis cycle is presented.

3 USE OF EXPERT KNOWLEDGE IN CHARGE CONTROLLERS

As already it has been mentioned, the operation of the stand-alone photovoltaic systems depends not only on the individual quality of the element that compose it, interaction between the components also contribute to system action [1]. In this sense, the charge controller is especially important.

On the same way, control strategies followed by the charge controller are very important factor that directly influence the maintenance and the useful lifetime of batteries. Special care should be paid on batteries because they influencing considerably (20%- 30%) [6] in the accrued cost of the installation.

In spite of the apparent simplicity in the operation of the load controllers, in practice, it is observed that load control in real system present a relatively high mistakes rate, that is, load controllers do not show some necessary quality requirements in photovoltaic systems [5]. This circumstance should be debt mainly, to the fact that the operation of these controllers does not take into account all aspects related to the load and discharge processes. Thus, when lead-acid batteries are used [2], it should be desirable to acquire certain operational characteristics; some of the most important ones can be expressed as follows:

a) Batteries that work in a high discharge rates, supply smaller capacities, since the internal transformations are superficial.
b) Low rate batteries discharge, increase their capacity since it is produced a better and more complete use of active materials and acid.
c) As temperature decreases, the battery capacity decrease, since the viscosity of the acid lowers and the diffusion ionic processes happen slower.
d) A positive aspect dealing with batteries, is that an adequate quantity of overcharge can avoid stratification problems.
e) As a result of the battery obsolescence, its internal resistance increases, therefore the maximum load tension would have to increase in order to maintain the same load regime.
f) It is interesting to accomplish flotation charges to preserve the batteries in a full charge state, even when they are not in operation; this action will compensate self-discharge losses.
g) The lower temperature and the higher charge rate, affect negatively the charge acceptance.

As can be appreciated, these are desirable operation characteristics. Nevertheless, they are not remarkably specific, these characteristics can be modelled using an expert system. In this way, a fuzzy controller can be obtained with a knowledge base, whose rules can represent the previously mentioned characteristics.

4 FUZZY CHARGE CONTROLLER

The structure of the Fuzzy Charge Controller (FCC) is showed in the figure 4.1. State of charge (SOC), generated current (Igen) and load current (Iload) are the FCC inputs. The FCC output will determine the charge controller operation mode. We have to point out, that the state of the charge (SOC) of the battery we are working with, has an estimated value at each time instant is a function of the quantity of current that each time instant stores the battery and the value of the corresponding capacity at the quiescent point [7]. Equally, it is important to indicate that switches S1 and S2 showed in the figure 4.1 are not ON-OFF type, actually they are continuous type.

For a given system characteristics to be controlled, it is only necessary to act on the overcharge and overdischarge states [9]. This circumstance will affect to the distribution of the Fuzzy sets, which will cover the mentioned states and the next zones.

The data base contains information on the Fuzzy sets associated with each variable, independently if it is an input or an output. These Fuzzy sets are shown in the figure 4.2. We have to indicate that the represented Fuzzy sets are normalized in the interval [0,1].

We have designed two knowledge bases, the first one will act in the overcharge states (switch S1) and the second one will work in the states of overdischarge (switch S2). These knowledge bases are represented in tables 4.1 and 4.2. It is important to point out that the knowledge bases represent a small subset of the existing knowledge in relationship to the conditions in which the battery would be charged and discharged.

Below, each rule of the two knowledge bases are explained:

Rule B1-R1: The battery state of charge is normal and therefore a fully charge of the battery is allowed.

Rule B1-R2: The battery state of charge is relatively high, and as the current generated by the photovoltaic generator is small, a fully charge of the battery is allowed.

Rule B1-R3: The battery state of charge is relatively high, the current generated by the photovoltaic generator is high, and the current consumed by the load is low. In this circumstance the charge controller allows a partial charge of the battery.

Rule B1-R4: The battery state of charge is relatively high, the current generated by the photovoltaic generator is high, and the current consumed by the load is relatively high. In this case, the charge controller allows a fully charge of the battery.

Rule B1-R5: The battery state of charge is relatively high and the current generated by the photovoltaic generator is high, the same as the current consumed by the load is relatively high. In this circumstance the charge controller permits a fully charge of the battery.

Rule B1-R6: The battery state of charge is very high, therefore it is convenient not to charge the battery.

For the overdischarge case, the knowledge base that it has been used is symmetrical to the previous one:

Rule B2-R1: If the battery state of charge is very low, the current is not allowed to arrive to the load.

Rule B2-R2: If the battery state of charge is relatively low and the current generated by the photovoltaic generator is high, it is permitted a fully energy consumption.

Rule B2-R3: If the battery state of charge is relatively low, the current generated by the photovoltaic generator is low and the current consumed by the load is also low, fully the energy consumption is allowed.

Rule B2-R4: If the battery state of charge is relatively low, the current generated by the photovoltaic generator is low and the current consumed by the load is normal, fully the energy consumption is permitted.

Rule B2-R5: If the battery state of charge is relatively low, the current generated by the photovoltaic generator is low and the current consumed by the load is high, it is allowed a partially energy consumption.

Rule B2-R6: If the battery state of the charge of the is high, fully the energy consumption is permitted.

5 SIMULATION RESULTS

Before the installation of the real Fuzzy charge controller, we have worked with some mathematical models to calculate the current delivered by the photovoltaic generator, as well as the behaviour of the accumulation system; these operations will test the kindness, and therefore the viability in the utilization of a Fuzzy charge controller. Below we have commented some aspects related to the used models.

5.1 Model of the photovoltaic generator:

The set of the modules that compose a photovoltaic system, constituents a unit designated as generation subsystem. From the modelling point of view, this element is the one that is mathematically better developed. These models are based on the solid-state physics. The problem we have to deal whit when modelling this subsystem consists on determining the parameters of the model. The equations that govern this model [7] are shown below.

(1)

where

(2)

(3)

The physical meaning of these parameters is explained in the following: I_G is the generated current, I_{SC} is the short circuit current of the cell, V_G is the battery tension, V_{OC} is the open circuit tension of the cell, R_{SG} is the serial resistance of the generator, R_S is the cell serial resistance, r_S is the normalized serial resistance, N_S is the number of cells of the generator serially grouped, N_P is the number of cells in parallel of the generator. A more detailed Information about the model of the photovoltaic generator can be found in [7].

5.2 Model of the accumulation system:

Special attention should be paid to the elected battery model, since it is the element that is intended to protect with the charge controller, so its correct modelling will directly affect the cogency of the obtained results. The battery model that has been used is proposed it by Copetti [2], this model represents precisely the variation of the main parameters of the battery during the charge and discharge processes. This model is composed by three submodel: one for the discharge process, other one for the charging and other one for the overcharge process. The mathematical expressions that constitute this model are exposed in the figure 5.1.

The results have been obtained simulating a 6Wp photovoltaic generator, and a 100Ah and 2V battery. The charge profiles considered have been from 19:00h to 24:00h with a 6Ah consumption for the overdischarge state and 2Ah for the overcharge state. For the radiation and temperature data, we have used real measured values in the locality of Jaén (Spain).

In the figure 5.2 are shown the simulation results obtained for the overcharge state. This figure includes simulation results using the Fuzzy charge controller and the serial charge controller. Equally, in the figure 5.3 the obtained simulation results for the overdischarge state are presented. These figures illustrate the time evolution during a 10 days period of: the state of charge, current of the battery (Ibat: difference between current generated and current consumed).

Some of the remarkable advantages that have been obtained using the Fuzzy Controller, is the increase of the quantity of current delivered to the battery, (negative Values of Ibat). Furthermore, the time evolution of the load state has been softened, this fact will allow a smaller battery deterioration.

6 REAL INSTALLATIONS

In order to compare operation results between the behaviour of a serial charge controller and the Fuzzy charge controller designed, we have installed two stand-alone photovoltaic systems, one with a conventional serial charge controller and the other one with the Fuzzy charge controller previously explained. In figure 6.1, a photograph is presented, where the photovoltaic generators of the installations are shown; these generators are embedded in a greater importance installation support structure. The other installations components are located in the laboratory of Photovoltaic Solar Energy of the Escuela Politécnica Superior of Jaén (Spain).

The global system structure installed is presented in figure 6.2. In this figure, the two stand-alone photovoltaic systems can be observed. The first one (SA-1), uses the serial charge controller, and the second one (SA-2), uses the Fuzzy charge controller. Below we described each of the elements that constitute the system.

6.1 Central computer:

It is the supervisor that centralizes all the interest data (Vbat1, Vbat2, Igen1, Igen2, Iload1, Iload2 and temperature) that are acquired in relation to the two photovoltaic systems, SA-1 and SA-2.

Furthermore, this computer is the one which works as Fuzzy charge controller, therefore in addition to storing all the previous data, it processes them to obtain the relative performance to the photovoltaic system with Fuzzy charge controller (SA-2). Once the performance is determined, the computer communicates through RS-232 to a μcontroller based system that acts on the stand-alone photovoltaic system SA-2. Therefore, in this development stage, the Fuzzy charge controller is located in the central computer, and it is not implemented on the μcontroller based system.

Though at present time, a computer and an data acquisition system for the behaviour analysis are being used, it is important to indicate, that under normal operation, the data acquisition system and the computer will not be necessary, that is to say, the whole system will be able to be implemented a commercial μcontroller based system.

6.2 Installation with conventional serial charge controller:

This installation is shown in the upper part of figure 6.2. In the following, the characteristics of the elements that constitute this installation are described.

Photovoltaic Generator: It is a photovoltaic module, its relevant electrical characteristics are: 12 volts of nominal voltage and a peak power value equal to 100 Wp.

Charge Controller: The model used in this experiment has been recently put into market. Its remarkable characteristics are the following:

- Use the SOC as a basic parameter in most of the control and regulation functions, (the calculation of the SOC is based on a proprietary algorithm).
- Incorporate an algorithm against overcharge, this feature assures soft charge process in the battery.
- The fall of tension in the line of the accumulator is compensated through the identification of the battery tension.

- Once a month during an hour interval, it accomplishes a supported charge with an increase of the final charge tension.
- Accomplish temperature follow-up procedure that forces a reduction in the charge final tension in high temperatures conditions, and an increase in low temperatures cases.

Accumulation System: the used accumulation system consists on a 45AH lead-acid battery and 12V nominal voltage.

6.3 Installation with Fuzzy charge controller:

This installation is shown in the lower part of figure 6.2. The characteristics of this installation are similar as those of the previous described. The only existing difference, evidently, consists on the charge controller.

As it has been commented, the central computer works as Fuzzy charge controller, which uses a μcontroller system as interface to other elements of the photovoltaic installation. More concretely, the function of this μcontroller system consists on providing the physical action on the power FETs that control, in a continuous way, the current flow that is injected to the load and the generated current flow. This action is based on the decisions taken by the Fuzzy charge controller, which are based on the readings accomplished by the available sensors in the μcontroller system.

6.4 Data acquisition system:

In addition to the different readings that are accomplished by the two charge controllers for the control operations, a data acquisition system exists, which monitors permanently all the remarkable magnitudes of both photovoltaic installations. These measures are used after the control operation to analyse the behaviour, and they are not taken into account during the normal operation. This data acquisition system is based on a Data Logger HP34970A.

7 REAL FUZZY CHARGE CONTROLLER

There are some differences between the real Fuzzy charge controller and the one that has been simulated. These differences are not of structural kind; they are forced changes that we have incorporated with the aim of improving the system global behaviour. Though, also they have been a consequence of some changes in the photovoltaic installations characteristics as compared to the simulated installation. One more time, we have to remark that the SOC values used are estimated values [7].

The Fuzzy sets used currently, are shown in figure 7.1. According to these Fuzzy sets, the battery state of charge begins to be high from 80%, and is considered low from 40%. The two Fuzzy sets for the generated current and the three Fuzzy sets for the load current, have been distributed in an uniform way. The Fuzzy sets related to the tension of the battery have been elected taking into account the tensions used in the histeresis cycle. The Fuzzy sets form of the consequent is more peculiar. This distribution is due to the not linearity found in the power FETs operation that control the currents flow, so that using this distribution, the power FET operation is partially linearizated. It is important to recall that the switches are not ON/OFF type, they work in a continuous fashion.

The knowledge base for the overcharge process is presented in table 7.1, meanwhile the knowledge base for overdischarge process is presented in table 7.2.

Below they are explained each rule of the two knowledge bases:

Rule B1-R1: When the battery tension is very high, the battery charge process is not allowed.

Rule B1-R2: When the battery tension is high and the state of charge is high, the battery charge process will not be permitted.

Rule B1-R3: Though the battery tension continues being high, the state of charge is not so high, therefore a mild battery charge process is allowed.

Rule B1-R4: This case is similar to the previous one, but with a smaller state of charge, therefore a greater battery charge process is authorized.

Rules B1-R5, R6, R7: Supposing the battery tension is not very high, the battery charge process is allowed, but not in a fully way.

For the overdischarge case, the knowledge base that has been used is symmetrical to the previous one, just as we pointed out in the simulation section:

Rules B2-R1, R2, R3: As long as the battery tension is not low, a fully energy consumption is allowed.

Rule B2-R4: When the battery tension is low, though the state of charge is high, only partial energy consumption is allowed.

Rule B2-R5: Upon having a battery with low tension and a normal state of charge, a low energy consumption is permitted.

Rule B2-R6: This situation is similar to the previous one, but now, the battery state of charge is low, this implies, energy consumption is not authorized.

Rule B2-R7: This rule is used to protect the battery, so that when the battery tension is very low, energy consumption will not be allowed.

8 OPERATION RESULTS

Making use of the Fuzzy charge controller described in previous section in a photovoltaic installation, a series of experimental results have been obtained. To explain these results, we will make use of a graph representation, see figure 8.1.

In figure 8.1, it is presented a comparison of the experimental data obtained in August 31st of 2001. In this figure we can appreciate the variations suffered by the generation and load currents are more softened in the system that uses the Fuzzy charge controller. This circumstance is especially relevant since the deterioration suffered by the battery is reduced. This fact can be also appreciated in the figure 8.2. This graph represents the battery tensions evolution.

It can be also observed that energy can be supplied during greater time intervals using the Fuzzy charge controller, though this supplied energy decreases, fundamentally in the time spaces, which is not supplied energy with the serial charge controller.

We can see more operation results in figure 8.3, concretely, this graph represent operation results of five consecutive days.

One more aspect to emphasize consists on the limitation of the overcharge intervals using the Fuzzy charge controller. We have to recall that the overcharge process is convenient (it provokes gasification that avoids the stratification phenomenon), but not for a long time period.

9 CONCLUSIONS

The Fuzzy charge controller proposed is an easy implementation controller and that improves of previous designs reliability. One of the most important characteristics of the Fuzzy charge controllers is the intrinsic flexibility of fuzzy controllers, which allow incorporating new knowledge with the alone incorporation of new rules in the knowledge base.

Concretely, there is a bunch of remarkable characteristics, derivated from the behaviour comparison to the described controllers (serial charge controller and Fuzzy charge controller):

The simulation results show the possibility of using Fuzzy control systems in the design of charge controllers for stand-alone photovoltaic systems. Not only it is possible, furthermore, Fuzzy charge controllers can be used with the objective of improving some of the stand-alone photovoltaic systems characteristics. This fact have been observed in the simulation tests, as well as, in the tests accomplished on the implemented installations. Particularly, we have been able to appreciate behaviours that allow us to predict a smaller deterioration suffered by the batteries in the system that uses the Fuzzy charge controller with the described knowledge bases.

As last conclusions, it is important to stress that though the current design is based on a computer, future implementations will be accomplished with the absence of this part. Equally, the use of the data acquisition system will be suppressed. The justification for these elements suppression is their price when we will have to face the development of a Fuzzy charge controller with characteristics of size and price similar to the commercial charge controllers.

Other aspect, at present time, we are working about, is the incorporation of a learning system using Genetic Algorithms [8][11], so that Genetic Algorithms could be generated knowledge bases in a automatic way in order to gain a better behaviour.

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KNOWLEDGE BASE FOR THE OVERCHARGE (B1)		
Nº	**ANTECEDENTS**	**S1**
R1	**IF** "SOC=N"	**H**
R2	**IF** "SOC=H" **and** "IGEN="L"	**H**
R3	**IF** "SOC=H" **and** "IGEN="H" **and** "ICAR=L"	**N**
R4	**IF** "SOC=H" **and** "IGEN="H" **and** "ICAR=N"	**H**
R5	**IF** "SOC=H" **and** "IGEN="H" **and** "ICAR=H"	**H**
R6	**IF** "SOC=VH"	**L**

Table 4.1: Knowledge base for the overcharge.

KNOWLEDGE BASE FOR THE OVERDISCHARGE (B2)		
Nº	**ANTECEDENTS**	**S2**
R1	**IF** “SOC=VL “	**L**
R2	**IF** “SOC=L” **and** “IGEN=”H”	**H**
R3	**IF** “SOC=L” **and** “IGEN=”L” **and** “ICAR=L”	**H**
R4	**IF** “SOC=L” **and** “IGEN=”L” **and** “ICAR=N”	**H**
R5	**IF** “SOC=L” **and** “IGEN=”L” **and** “ICAR=H”	**N**
R6	**IF** “SOC=N”	**H**

Table 4.2: Knowledge base for the overdischarge.

KNOWLEDGE BASE FOR THE OVERCHARGE (B1)		
Nº	**ANTECEDENTS**	**S1**
R1	**IF** “Vbat=VH“	**VL**
R2	**IF** “Vbat=H” **and** “SOC=H”	**VL**
R3	**IF** “Vbat=H” **and** “SOC=”M”	**L**
R4	**IF** “Vbat=H” **and** “SOC=”L”	**M**
R5	**IF** “Vbat=M”	**H**
R6	**IF** “Vbat=L”	**H**
R7	**IF** “Vbat=VL”	**H**

Table 7.1: Knowledge base for the overcharge.

KNOWLEDGE BASE FOR THE OVERDISCHARGE (B2)		
Nº	**ANTECEDENTES**	**S2**
R1	**IF** “Vbat=VH”	**H**
R2	**IF** “Vbat=H”	**H**
R3	**IF** “Vbat=M”	**H**
R4	**IF** “Vbat=L” **and** “SOC=”H”	**M**
R5	**IF** “Vbat=L” **and** “SOC=”M”	**L**
R6	**IF** “Vbat=L” **and** “SOC=”L”	**VL**
R7	**IF** “Vbat=VL”	**VL**

Table 7.2: Knowledge base for the overdischarge.

Figure 2.1: Structure of a Stand-Alone Photovoltaic System.

Overcharge Histeresis cycle.
Figure 2.2:

Figure 2.3: Overdischarge Histeresis cycle.

Figure 4.1: Structure of the Fuzzy charge controller.

Figure 4.2: Fuzzy set of Fuzzy charge controller.

Figure 5.1: Copetti battery model [2].

Figure 5.2: Overcharge process simulation.

Figure 5.3: Overdischarge process simulation.

Figure 6.1. Photovoltaic generators and Solar Energy Laboratory.

Figure 6.2: Global system structure.

Figure 7.1: Fuzzy set of real Fuzzy charge controller.

Figure 8.1: Comparison of experimental results. (I).

Figure 8.2: Comparison of experimental results. (II).

Figure 8.3
: Operation results during 5 consecutive days.