A. Daoud
A. Midoun

J. Electrical Systems 1-1 (2005): 62-72

Regular paper

Fuzzy Control of a Lead Acid Battery Charger

Journal of Electrical Systems

In this paper, an alternative battery charging control technique based on fuzzy logic for photovoltaic (PV) applications is presented. A PV module is connected to a buck type DC/DC power converter and a microcontroller based unit is used to control the lead acid battery charging voltage. The fuzzy control is used due to the simplicity of implementation, robustness and independence from the complex mathematical representation of the battery. The usefulness of this control method is confirmed by experiments.

Keywords: Fuzzy controller, PV module, Buck converter, Microcontroller, Lead acid battery.

1. INTRODUCTION

The photovoltaic systems make possible to exploit the sun energy at various ends. They are highly reliable and constitute a nonpolluting source of electricity, which can be appropriate for many applications. The autonomy of these systems will require batteries to store the electrical energy produced by the PV modules and to restore it during the nights periods and those of weak irradiation. The lead acid battery, although known for more than one hundred years, has currently offered the best response in terms of price, energetic efficiency and lifetime.

The main function of a controller or regulator in PV system is to fully charge the battery without permitting overcharge [1] while preventing reverse current flow at night. If a non-self-regulating solar array is connected to lead acid batteries with no overcharge protection, battery life will be compromised. Simple controllers contain a transistor that disconnects or reconnects the PV to the charging circuit once a pre-set voltage is reached. More sophisticated controllers utilize pulse width modulation (PWM) to assure the battery is being fully charged. The first 70% to 80% of battery capacity is easily replaced, but the last 20% to 30% requires more attention and therefore more complexity. This complexity is avoided by using a skilled operators experience in the form of rules. Thus a fuzzy control system seeks to control the battery that cannot be controlled well by a conventional control such as PID, PD, PI etc., due to the unavailability of an accurate mathematical model of the battery. In this paper

Corresponding author : d_elamine@yahoo.com
Laboratoire d'Electronique de Puissance et Energie Solaire, Institut d'Electronique, U.S.T.O, B.P 1505, Oran, Algérie.

design of an intelligent battery charger, in which the control algorithm is implemented with fuzzy logic is discussed. The digital architecture is implemented with Microchip's 8-bit microcontroller PIC16F877, where the fuzzy controller reads the voltage of the battery to determine the state of charge and then controls the amount of current flowing into the battery by using a DC to DC buck converter.

2. CHARGE CONTROLLER DESIGNS

Two basic methods [2] exist for controlling or regulating the charging of a battery from a PV module or array -*shunt* and *series* regulation. Simple designs interrupt or disconnect the array from the battery at regulation, while more sophisticated designs limit the current to the battery in a linear manner that maintains a high battery voltage.

2.1 Shunt controller design

Since photovoltaic cells are current-limited by design, PV modules and arrays can be short-circuited without any harm. The ability to short-circuit modules or an array is the basis of operation for shunt controllers. Fig1.(a) shows an electrical design of a typical shunt type controller. The shunt controller regulates the charging of a battery from the PV array by short-circuiting the array internal to the controller. All shunt controllers must have a blocking diode in series between the battery and the shunt element to prevent the battery from short-circuiting when the array is regulating. Because there is some voltage drop between the array and controller and due to wiring and resistance of the shunt element, the array is never entirely short circuited, resulting in some power dissipation within the controller. For this reason, most shunt controllers require a heat sink to dissipate power, and are generally limited to use in PV systems.

The regulation element in shunt controllers is typically a power transistor or MOSFET, depending on the specific design. There are a couple of variations of the shunt controller design. The first is a simple interrupting, or on-off type controller design. The second type limits the array current in a gradual manner, by decreasing the resistance of the shunt element as the battery reaches full state of charge.

2.2 Series controller designs

As the name implies, this type of controller works in series between the array and battery, rather than in parallel as for the shunt controller.

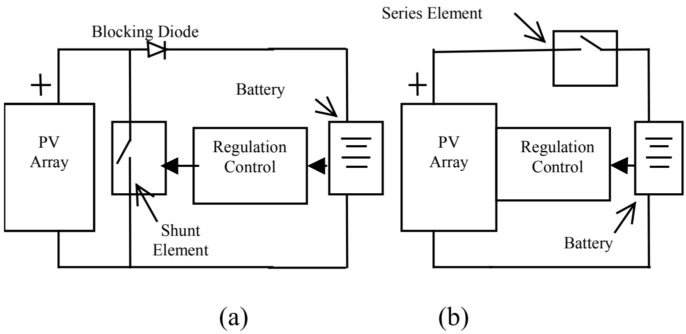

Fig.1 Regulator designs: (a) Shunt Controller, (b) Series Controller

While this type of controller is commonly used in small PV systems, it is also the practical choice for larger systems due to the current limitations of shunt controllers. Fig 1.(b) shows an electrical design of a typical series type controller. In a series controller design, a relay or solid-state switch either opens the circuit between the array and the battery to discontinuing charging, or limits the current in a series-linear manner to hold the battery voltage at a high value. In the simpler series interrupting design, the controller reconnects the array to the battery once the battery falls to the array reconnect voltage set point. As these on-off charge cycles continue, the 'on' time becoming shorter and shorter as the battery becomes fully charged. Because the series controller open-circuits rather than short-circuits the array as in shunt-controllers, no blocking diode is needed to prevent the battery from short-circuiting when the controller regulates.

The series-interrupting pulse width modulated (PWM) regulator uses a semiconductor switching element between the array and battery which is switched on/off at a variable frequency with a variable duty cycle to maintain the battery at or very close to the voltage regulation set point. Similar to the series-linear, power dissipation within the controller is considerably lower in the series interrupting PWM design. By electronically controlling the high speed switching or regulation element, the PWM controller breaks the array current into pulses at some constant frequency, and varies the width and time of the pulses to regulate the amount of charge flowing into the battery. The PWM design allows greater control over exactly how a battery approaches full charge and generates less heat.

3. METHODS OF CHARGING LEAD ACID BATTERIES

The lead-acid charging process is somewhat lenient as long as it is not overcharged, overheated, or allowed to form excessive gas. Methods for lead-acid battery charging vary considerably. The various charge methods are:

1. Constant current
2. Semi-constant current
3. Constant-voltage
4. Pulse charge
5. Trickle charge
6. Float charge
7. Rapid charge

The first method is rarely used in general application, but is very effective when charging a large number of serially connected batteries. This method has a small coefficient of efficiency and adversely effect over the characteristics of the battery and the durability, while the second method has very simple architecture consisting of a transformer, rectifier bridge and a current limiting resistor. This method is also called as "Taper charging" and it is also not recommendable due to constant current characteristics of the charging device adversely effect the lead acid battery. Battery is normally overcharged due to the very high current which reduces the battery life.

The constant-voltage method Fig.2 applies a given voltage value allowing the current to vary. The fourth method applies a current to the battery for a fixed length of time, disconnects from the circuit and measures the open circuit voltage to determine the state of charge, then resumes as required to complete the charge process. The fifth method applies a continuous constant low current to maintain charge which is required because of self discharge, while the sixth method is similar to trickle charging and uses a constant voltage. The last method applies varying techniques to accomplish charging in a reduced time period. In order to accomplish this method successfully, tight controls are needed to maintain proper charge parameters such as temperature and cell voltage not exceeded.

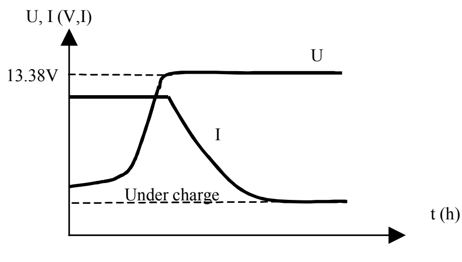

Fig.2 Charging with a constant

In general, the algorithms of charge use a combination of constant current method and the constant voltage charging. This charge is started with constant current until a predetermined voltage is reached, then the charger moves onto the second method. The latter algorithm can be improved by using fuzzy control, where the initial charging current is high (10% -25% of the capacity of the battery) in order to reduce the charging time. When the battery charging voltage approaches the set point, then the charging current decreases minimizing overcharge, grid corrosion associated with overcharge and water loss by electrolysis of the electrolyte.

4. FUZZY CONTROL

In linear control, there are three-term controllers: PD, PI and PID, which are expressed mathematically as:

$$U_{PD} = K_P e + K_D \dot{e} \tag{1}$$

$$U_{PI} = K_P e + K_I \int e dt \tag{2}$$

$$U_{PID} = K_P e + K_I \int e dt + K_D \dot{e} \tag{3}$$

where e is the error (set point - output), $\dot{e}$ is the derivative of error. The gains K_P, K_I and K_D are called proportional gain, integral gain and derivative gain.

In fuzzy control, there are analogous PD type Fuzzy Logic controller (FZ-PD), PI type Fuzzy Logic controller (FZ-PI), and PID type Fuzzy Logic controller (FZ-PID). Their basic structures [3] are shown in Fig.3.

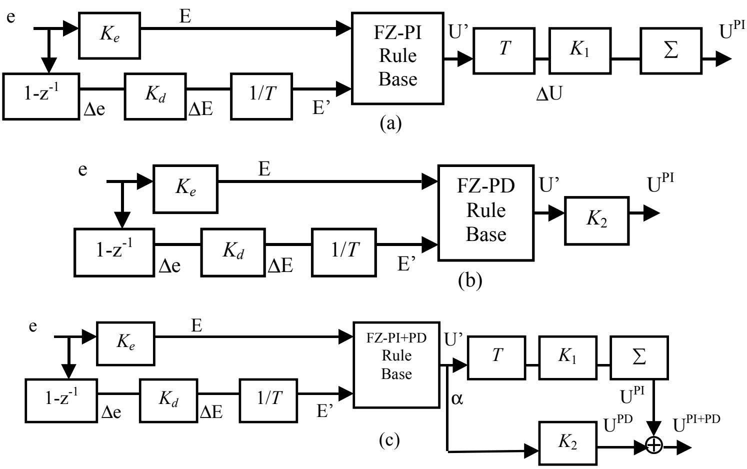

Fig.3: Digital Structure of : (a) FZ-PI, (b) FZ- PD, (c) FZ-PI+PD

K_e and K_d are input scaling gains. K_1 and K_2 are the output scaling gains. The fuzzy inputs parts are the error e(k) and the change of the error Δe(k), which are discretized as follows:

$$e(k) = \text{Setpoint}(k) - \text{Output}(k) \tag{4}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{5}$$

The output of FZ-PI and FZ-PD can be expressed as:

$$U^{PI}(k) = K_1 \sum f\left(K_e e(k), \frac{K_d \dot{e}(k)}{T} \right) \tag{6}$$

$$U^{PD}(k) = K_2 f\left(K_e e(k), \frac{K_d \dot{e}(k)}{T} \right) \tag{7}$$

$f(.)$ represents the fuzzy operation. The three blocks used to define the fuzzy algorithm proposed are:

1: Fuzzification block;

2: Inference block;

3: Defuzzification block.

As shown in Fig.4, seven fuzzy subsets PB (Positive Big),PM (Positive Medium), PS (Positive Small), ZR (Zero), NS (Negative Small), NM (Negative Medium), NB (Negative Big) have been chosen for inputs variables (e(k), Δe(k)) and the output variable α(k).

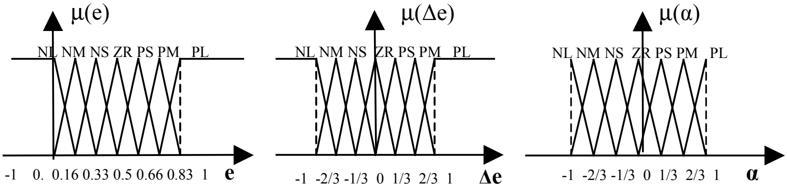

Fig.4: Membership Functions

The design of fuzzy rules involves writing rules that relate the inputs variables to the output variable. These rules are expressed as IF-THEN statements and the syntax is as follows:

IF e(k) is PB AND Δe(k) is PB THEN α(k) is PB.

The fuzzy rules base [4] used for the lead acid battery charging voltage control is show in Table 1. For further reduce the complexity of the fuzzy rules base design and increase efficiency, both FZ-PI and FZ-PD parts share a common rules base. A PI control is normally more important for steady state performance. The Mamdani method is used in the fuzzy inference and the center of gravity (COG) defuzzification method to calculate the output α(k). Then FZ-(PI+PD) control can be expressed in the equation below.

$$U^{PI+PD}(k) = U^{PI}(k) + U^{PD}(k) \quad (8)$$

Table 1: Fuzzy Rules Base

Δe \ e	NL	NM	NS	ZR	PS	PM	PL
PL	ZR	PS	PM	PL	PL	PL	PL
PM	NS	ZR	PS	PM	PL	PL	PL
PS	NM	NS	ZR	PS	PM	PL	PL
ZR	NL	NM	NS	ZR	PS	PM	PL
NS	NL	NL	NM	NS	ZR	PS	PM
NM	NL	NL	NL	NM	NS	ZR	PS
NL	NL	NL	NL	NL	NM	NS	ZR

5. CONTROL CIRCUIT OPERATING

A detailed block diagram of the proposed system is shown in Fig.6. It comprises a PV module LA361K51-KYOCERA ($V_{OpenCircuit}$=21.2V ; $I_{ShortCircuit}$=3.2A ; OutPut=50W) feeding a battery as load and controller card. The buck converter is suitable for use when the solar module voltage is high and the battery voltage is low.

- The control unit consists of a Microchip 16F877-20/P microcontroller and interface circuits required to lead the battery voltage and current signals to the microcontroller.

The controller on-chip 8-bit PWM generator output drives the DC/DC buck converter, according to the battery charging algorithm. The buck converter comprises: MOSFET switch IRF740, 1N5408 freewheeling diode (D) and LC filter. Consequently a rectangular shaped voltage appears on the diode (D) cathode and this is then filtered by the L-C-D network and converted into a continuous mean value across the capacitor C and therefore across the battery. The switching frequency (20KHz) is designed to obtain a low output ripple. Since the voltage across the inductor at any time can be calculated based on :

$$V_L = L\frac{dI_L}{dt} \quad (9)$$

The inductor value [5] can be calculate from

$$L = \frac{(V_I - V_0)V_0 T}{V_I \Delta I_L} \tag{10}$$

where T : switching period, V_I: input voltage (solar module), V_0 : output voltage et ΔI_L : inductor current ripple.

To calculate the output capacitor value [6], we can use the following formula:

$$C = \frac{(V_I - V_0)V_0}{8V_I \Delta V_C f^2 L} \tag{11}$$

where f : switching frequency, ΔV_C: capacitor voltage ripple.

A blocking diode D_e (1N5408) is connected in series with the PV module to prevent reverse current and the capacity C_T is used for reducing the module voltage ripple. The battery voltage is measured by means of a voltage divider and differential voltage operational amplifier. The output of the previous block is applied to a second order low pass filter with a 40 db/dec attenuation and a cut-off frequency of 100Hz. The output of the filter is interfaced to an operational amplifier based voltage-follower, and a hall-effect based current sensor is used to sense the battery charging current Fig.6. To implement the serial communication with the PC which has a display program of the battery charging voltage and current, the only component needed is a line driver and receiver chip (MAX232).

6. EXPERIMENTAL RESULTS

The battery charging method based on fuzzy (PI+PD) control was laboratory tested with a PV module charging 12V, 24Ah nominal capacity sealed Valve Regulated Lead Acid battery. The primary function of the fuzzy (PI+PD) charge controller in the stand-alone PV system is to protect the battery from overcharge. According to the battery charging voltage, the controller generates a command representing the duty cycle given by the microcontroller PWM pin. The PWM signal is applied to the MOSFET driver, amplified and injected between gate terminal and source terminal of the international rectifier N-channel IRF740 which can hold a maximum drain to source voltage of 400V and can pass a maximum current of 10A.

The PV module power will switch according to the switching signal generated by the microcontroller PWM pin. The initial current provided by the PV module depends on its operating point. During the charge cycle, the PV module current [7] decreases and its voltage moves towards the area where it behaves like a voltage source Fig.5. The initial charge current Fig.7 is high (Average Irradiation= 610w/m^2, Average Temperature=28°C) keeping almost the same value as long as the charging voltage is far from the set point (13.65

Volts). As the battery voltage rises Fig.8, the pulse width is decreased, effectively reducing the magnitude of the charge current. When the battery voltage approaches the set point, the charging current decreases quickly allowing to keep the charging voltage at a value close to the set point.

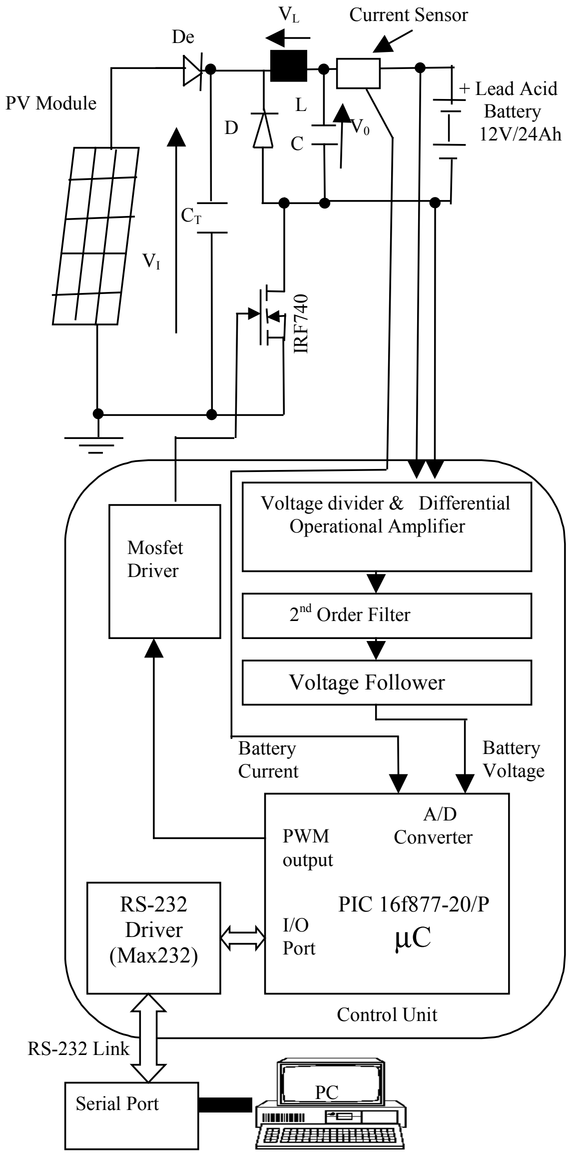

Fig. 6: Detailed diagram of the proposed system.

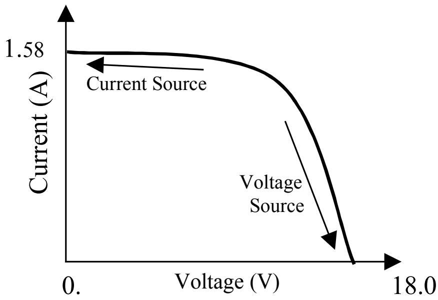

Fig.5: PV Module IV

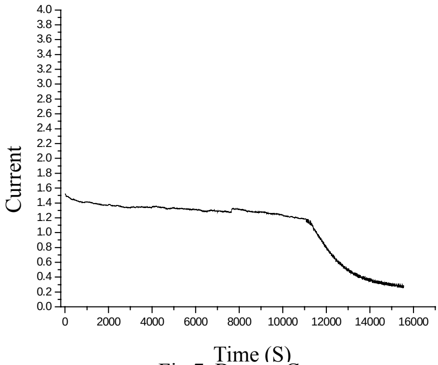

Fig.7 Battery Current

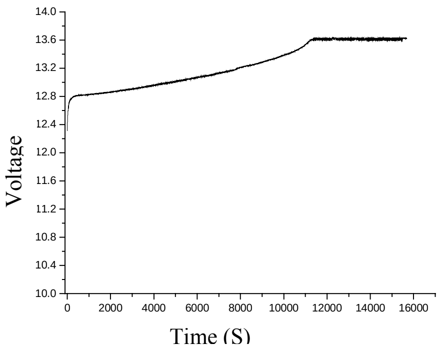

Fig.8 Battery Voltage

6. CONCLUSION

This work is a contribution to the development of a fuzzy logic based controller to provide voltage charge control to a lead acid battery in a stand-alone PV system. By using fuzzy PI rules base, the FZ-(PI+PD) controller generates a duty cycle converted on PWM signal, delivered by the microchip microcontroller, to provide the switching control for the MOSFET in the buck converter circuit. The FZ-(PI+PD) algorithm is an improvement of the constant voltage charging combined with the constant current method. The charging algorithm allows to charge the lead acid battery with a high initial PV module current and as the charging voltage go up to set point, the charging current decreases according to the fuzzy rules in order to allow to the battery voltage to reach the full charge without overcharge. All components used in the control unit card and the buck converter card are available with cheapest price. An LCD module can be added to the control card for the display of the charging current and voltage

7. REFERENCES

[1] Kyocera Solar. Inc, Understanding solar, *http://www.kyocerasolar.com/learn/*

[2] J. P. Dunlop, Batteries and charge control in stand-alone photovoltaic systems : Fundamentals and application, Report Prepared for Sandia National Laboratories, Florida Solar Energy Center, Jan 1997.

[3] P. Pivonka and J. Zizka, The use of fuzzy pi/pd/pid controllers in fuzzy control", Third European Congress on Intelligent Technique and Soft Computing, Vol.2, 28-31, Aug. 1995, pp. 1041-1045.

[4] H-X Li and H. B. Gatland, Conventional fuzzy control and its enhancement, IEEE Transactions on Systems, Man & Cybernetics, Vol. 26, no. 5, pp. 791-797, Oct 1996.

[5] SGS Thomson Microelectronics, Designing with the L296 monolithic power switching regulator", Application Note. *http://www.salleurl.edu/cedei/hardware/power/ 4269.pdf*

[6] Power Designers, Switch mode power supply: Basic circuit operation, *http://Powerdesigners.com/InfoWeb/resources/Pe.html/ch07s1/bas-cht.htm*

[7] A. Daoud, A. Midoun, Commande floue de la charge d’une batterie dans une installation photovoltaïque, International Congress on photovoltaïc and Wind Energies ICPWE'2003, Dec 2003.