An intelligent lead-acid battery closed-loop charger using a combined fuzzy controller for PV applications

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Abstract. This paper presents the modeling of an intelligent combined MPPT and Lead-Acid battery charger controller for standalone solar photovoltaic systems. It involves the control of a DC/DC buck converter through a control unit, which contains two cascaded fuzzy logic controllers (FLC), that adjusts the required duty cycle of the converter according to the state of charge and the three stage lead acid battery charging system. The first fuzzy logic controller (FLC1) consists of an MPPT controller to extract the maximum power produced by the PV array, while the second fuzzy controller (FLC2) is aimed to control the voltage across the battery to ensure the three stage charging approach. This solution of employing two distinct cascaded fuzzy controllers surmounts the drawbacks of the classical chargers in which the voltage provided to the lead acid battery is not constant owing to the variable MPPT voltage and increasing the battery’s lifespan. Therefore, this control strategy maximises the power provided by the PV array, extends the battery’s life cycle by preventing the overcharge incurred by the MPPT controller and mitigates the disadvantages and limitations of the traditional solar chargers.

1 Introduction

Batteries power supply and their charge control systems have generally been recognized as the heart of PV applications [1]. In this context batteries must have a good cycling efficiency and an effective depth of discharge level. As more of a bridge between the PV array and the load, a DC-DC converter is always used, with its duty cycle varies to ensure that the PV panel performs at the maximum power point(MPP).

In the literature, various strategies of the maximum power point tracking (MPPT) have been carried out, that can be ranked into the following classification[2],[3]: classical MPPT techniques, MPPT strategies on the basis of Artificial Intelligence (AI), and MPPT techniques based linear and non-linear controllers [4]. Among the most widely used MPPT techniques, namely the classical Perturb and Observe (P & O) Algorithm, incremental conductance (IncC), neuro-fuzzy and neural network methods [5, 6]. Many researchers are involved in the fuzzy-logic-controller based MPPT strategy [7],[8],[10]. In this way, it has been confirmed that the Fuzzy Logic (FL) control technique-based MPPT outperforms the traditional MPPT techniques under variable weather conditions in terms of robustness and accuracy [9].

In this paper, two cascaded fuzzy controllers are used to increase the system’s efficiency and accuracy. The first one FLC1 is responsible to extract the MPP from the PV array, in the other hand, another fuzzy logic controller FLC2 is used for the purpose of performing as a lead-acid battery charge controller, in order to avoid battery damage incurred by variable MPPT voltage and increasing the battery’s lifespan.

2 Methodology

Figure 1 describes the schematic diagram of the standalone photovoltaic based MPPT battery charge controller system, which is developed in Matlab/Simulink™. The system is composed of a PV array linked directly to the DC connection, as well as an integrated power buck converter connected to a lead acid (Le-A) battery. An MPPT charge block controller is composed of two fuzzy systems, the first one is the FLC1 includes a fuzzy logic block based MPPT controller, it is used to extract the full amount of power supplied by the photovoltaic generator. The second stage of the controller is another fuzzy voltage regulator block (FLC2) based on the three stage-charging technique, which ensures the regulation of the voltage across the Le-A battery.

2.1 PV Modeling

A solar photovoltaic cell is composed effectively of a PN semiconductor-junction that transforms illumination energy to electrical energy [11]. The solar cell can be illus-
Table 1. SY-270W panel’s parameters

| PV Data                  | Unit | Value |
|--------------------------|------|-------|
| Maximum power            | W    | 270   |
| Current at the MPP       | A    | 7.44 A|
| Voltage at the MPP       | V    | 36.28 |
| Open-Circuit Voltage    | V    | 43.63 |
| Short-Circuit Current    | A    | 7.96  |

trated by a voltage-controlled current source that presents the temperature and solar emission sensitive, in parallel with one diode and a shunt-resistor Rs and in series with a connected resistor Rs [12]. After being a simplistic model, this analogous circuit is precise enough to reflect the various forms of photovoltaic cells. The numerical analysis of solar cells is described in depth in [13]. Figure 2 presents a single diode model configuration.

As light comes upon it, the PV panel functions as a current source, PV array are a series-parallel combination of solar cells. In this context, the PV array used in this research consists of eight (SY-270W) Shenzhen Sunshine module connected in series as shown in the figure 3. The parameters of the used module are presented in Table 1.

A design for the industrial used module has been developed in order to achieve more practical conditions for the performed simulations.

The SY-270W PV module characteristic is illustrated in figure 4 at a various amounts of irradiation and temperature.

2.2 DC/DC Buck converter Modeling

The buck converter was preferred in order to transform and regulate the high supply voltage into the required low Lead battery voltage[14]. The figure 5 corresponds to the average model of the DC-DC buck converter on the basis of the internal and output capacitors Cin and Co. S and Lb are respectively the controlled mosfet and the inductance, where the input/output voltages are respectively Vin & Vout. The buck parameters are calculated as follow:

\[ V_{out} = V_{in} \times D \]  
\[ L_b = \frac{V_{out} \times (1 - D)}{\Delta I \times f} \]
A single diode model configuration of solar cells is described in depth in [13]. Figure 2 presents the analogous circuit is precise enough to reflect the variation in temperature and solar emission sensitive, in parallel connected resistor $R_s$ [12]. After being a simplistic model, the performed simulations.

As light comes upon it, the PV panel functions as a voltage-controlled current source that presents figure 4 at a various amounts of irradiation and temperature.

Figure 1. A design for the industrial used module has been designed.

Photovoltaic Cell

PV array

PV battery charger control diagram

PV curves of SY-270W panel's parameters

Photovoltaic panels installed in the laboratory

Figure 2. three stages Le-Acid battery charging process

3.2 Description of the fuzzy logic controllers

3.2.1 First fuzzy logic stage based MPPT

Currently, MPPT-based Fuzzy-Logic controller has become a suitable strategy of control for PV systems. The Fuzzy control approach needs no accurate model awareness, and it consists of three steps: (fuzzification, fuzzy rules and defuzzification) [18]. The controller’s inputs are always the combination of the error and error variation. In the fuzzification stage, input parameters are transformed on the basis of several specified member functions into linguistic variables, the next stage (fuzzy rules) involves manipulation of these linguistic factors which are presented in the tables 2 and 3, relying on laws based on the if & then principle that are driven by the system’s ideal behaviour. In the final phase (defuzzification), the FLC control transforms linguistic variables on the output of membership.
functions to numerical variables. The following equations presents the two Inputs of the first controller FLC1 designed for MPPT:

$$\zeta(n) = \frac{\delta P}{\delta V} = \frac{P(n) - P(n-1)}{V(n) - V(n-1)}$$  \hspace{1cm} (4)

$$\Delta \zeta(n) = \zeta(n) - \zeta(n-1)$$  \hspace{1cm} (5)

The output is the difference in the duty cycle $D_k$ that changes obviously the DC-DC converter efficiency as a result in the Equation 6:

$$\Delta D_k = \frac{\sum A_i Y_i}{\sum A_i} \delta \zeta_k$$  \hspace{1cm} (6)

Where, $\zeta_k$ is the slope power $P_{pv}$ and voltage $V_{pv}$ change, $\Delta \zeta_k$ is the change of $\zeta_k$, and the minimum of membership is $Ai$ where $Ai = \min [\text{Memberships & rules}]$ .

The five subsets memberships used in the FLC 1 are positive big, positive small, zero, negative small and negative big respectively P,B- P,S-ZE-N,S and N,B.

### 3.2.2 Second fuzzy logic stage based voltage regulator

This phase controls the battery output voltage with the usual voltage of the DC/DC buck converter through the second fuzzy logic unit named FLC2, which uses as inputs the error $\zeta'$ and the error change $\Delta \zeta'$ of the voltage difference across the battery as shown in the following equations:

$$\zeta'(n) = V_{RE}(n) - V_B(n)$$  \hspace{1cm} (7)

$$\Delta \zeta'(n) = \zeta'(n) - \zeta'(n-1)$$  \hspace{1cm} (8)

$$\Delta D'_{n+1} = FLC_2 [\zeta'(n)]$$  \hspace{1cm} (9)

Where $V_{RE}$ is the needed charging voltage, $\Delta D'_{n+1}$ is the output of the FLC2.

### 4 Results and discussion

In this paper, MATLAB/Simulink$^{TM}$ software was used to design and model the entire structure depicted in the scheme presented in the first section. Table 1 lists the numerical values of the SPV panel used in the simulation with a peak power of 270W. The improved cascaded charge controllers based on FL control are presented in the previous section, they control directly the power DC/DC buck converter. The behaviour and reliability of the cascaded controllers are examined and evaluated.

#### 4.1 First FLC MPPT stage

The first stage of the cascaded FL control is investigated by the presented solar irradiance profile in the figure 8, and it varies between 0-1000 W/m$^2$. The brusque change in solar insolation profile was divided for this rigorous study into six states. The atmospheric temperature is constant at 25°C. The efficiency and the behaviour of the first stage FLC1 were determined and compared with two common traditional MPPT methods: P&O and IncCond [19]. The efficiency is determined according to the following equation:

$$\eta = \frac{\int_0^T P_{array}}{\int_0^T P_{MPPT}} \times 100$$  \hspace{1cm} (10)

Figure 8 demonstrates the performance for each irradiance state of the compared MPPT strategies. Table 4 summarizes the results obtained for the different controllers. It can be observed that the FLC1-MPPT gives a better result in terms of dynamic response and power ripples compared to the other MPPT controllers.

#### 4.2 Second FLC charge controller stage

The battery charge controller’s output is demonstrated by charging the battery sequentially through bulk stage, absorption stage, and float charging level. This demonstrates
Table 4. Comparison of the performance for the MPPT controllers at STC

|           | P & O | FLC1 | IncCond |
|-----------|-------|------|---------|
| Rising time(s) | 0.188 | 0.12 | 0.202   |
| Power ripples(w) | 0.8   | 0.07 | 0.62    |
| Efficiency %   | 99.81 | 99.91| 99.88   |

Figure 9. Power extracted of the SY-270W with different controller

the Le-A battery’s three-stages charging levels. The PV array used in this paper includes eight SY-270W Shenzhen Sunshine panels (4 modules connected in series x 2 modules connected in parallels) which provides 2160 W at the STC. The PV array is also tested under solar irradiance variation and constant temperature as seen in the figures 10 and 11.

Figure 10. Irradiance profile of the 2,16 kw PV array

The used battery in the first test is an 100 AH, 48V Le-A battery bank and it consists of a set of four 12V Le-A batteries connected in series, the state of charge (SoC) is set to 99.8%. Moreover, the reference voltage for the FLC 2 regulator is fixed at Vref = 55.5V for the absorption stage, while in the second test, we used two 12V Le-A batteries connected in series. The figures 12 and 13 present the performance of the studied Le-A batteries at the standard test condition STC, where the variation of current, SoC and voltage are presented.

The figure 12 shows the change of the voltage, current and SoC of the five Le-A batteries associated in series, where the temperature and solar irradiance are fixed in 25°C and 1000W/m². The discussed three stages charging levels are clearly seen. In case of the test based on five Le-A batteries, for the first state shown in the figure 12 where 0 s < t < 84 s, The proposed controller operates in the MPPT stage. As a result, the battery absorbs all of the power provided by the PV array, thus, when the battery SoC is under 100% and the battery voltage is lower than Vb-ab then the charging process operates in the bulk stage. When the battery voltage achieves Vb-ab = 55.5 V after 84 seconds, the charger switches to the absorption charging level based regulated voltage. In this stage, the power provided by the PV array is decreased to maintain the regulated voltage in the absorption mode operation and to reduce the amount battery’s current. At 262 sec when the SoC achieves 100%, the proposed controller moves to the float operation level in which the battery voltage decreases to the floating voltage where Vb-fj = 52.4 V.

Figure 13. shows the parameters of the battery bank in the case of the second test, where the battery bank is composed of two Le-A batteries coupled in series at the
Figure 13. The Le-A Battery performance of the second test standard test conditions. The three stages charging mode are clearly seen. The initial SoC is set to 99.6%. In the first phase, the controller performs in the FLC1 (MPPT mode) until the battery voltage reaches the reference voltage $V_{b-ab}=27.7$V at $t=18$s. When $18<s<52$s, the battery voltage is regulated at the absorption voltage 27.7 V where the battery current is automatically decreased via FLC2. The battery SoC reaches 100% at 52s, then the FLC2 adjust the reference voltage again at $V_{b-fl}=25.9$V, in this phase, to prevent self-discharge and to guarantee 100% of SoC, only a limited current is provided.

5 Conclusion

In this paper, an intelligent lead acid battery charger controller is proposed for PV application. Pursuant to the charging operation mode, the proposed technique allows the system to operate in the perfect conditions. Thus, the controller is a combination of two fuzzy controllers(MPPT and the charge controller). The results have shown that the FLC1 based MPPT methodology delivers an outstanding performance in comparison with the classical approaches P&O and IncCon in terms of the efficiency and rising time, while the second fuzzy controller FLC2 operates as a voltage charge regulator. Furthermore, the findings of simulations were presented for various battery sizes where the three-states charging mode are clearly seen. This strategy ensures that the battery operates within a safe voltage range in the proper mode of the three-stage battery charging. The suggested charging technique decreases the restricted charging time while also increases the battery’s lifespan.

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