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Design of a photovoltaic MPPT charge controller using DC-DC ZETA converter with a modified three-stage charging method

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ABSTRACT

Nowadays, one of the primary kinds of renewable energies is photovoltaic (PV) systems. In standalone PV systems, the battery charge controller plays an important role in the system efficiency. In the maximum power point tracking (MPPT) charge controller, due to adjusting the voltage level and tracking the maximum power, DC-DC converter and MPPT algorithm are used. ZETA converter, as a DC-DC converter, offers a low output ripple. In the proposed MPPT charge controller, a DC-DC ZETA converter accompanied by a perturb and observe (P&O) algorithm will be used for tracking maximum power. Furthermore, over-charging and gassing are phenomena that may reduce the battery life by increasing the battery's temperature. To overcome this obstacle, the proposed three-stage charging method, which is the battery charging voltage levels (bulk, absorption, and float) are based on the battery temperature. The proposed MPPT charge controller is used for providing lower temperature for the battery when being charged. By comparing the proposed MPPT charge controller with the conventional method, the simulation results can ensure the desired performance of the proposed charge controller.

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1. INTRODUCTION

Today, renewable energy resources constitute a critical element in electricity generation [1]-[3]. The PV systems are among renewable energy resources that have been significantly considered research-oriented projects. PV systems can be used grid-connected or standalone. Components of the standalone system include panel, charge controller, battery, and inverter. In these systems, the charge controller is a vital part for prolonging the battery life and reducing the system cost. High temperature, over-charging, and under-charging can reduce the lifespan of the battery [4]. Under-charging causes sulfating while over-charging increases temperature lead to gassing and stratification in the battery. Under-charging is mostly common in PV systems due to periods of low radiation intensity. When gassing occurs in the battery (gas is removed from the battery), the electrolyte level decreases in the battery. In addition, the presence of ripple components in the charge controller causes the amount of current or voltage to exceed the allowable gassing threshold leading to considerable harm to the battery. In lead-acid batteries, the gassing starts at about 2.3 volts per cell (at 25 $C°$), which varies according to the battery and ambient temperature. To prevent the gassing effect, the charging current must be reduced when it reaches the gassing threshold. Therefore, understanding these effects is necessary for designing a suitable charge controller.

It is possible to divide the solar charge controllers into four major classes: shunt type, series type, pulse width modulation (PWM), and maximum power point tracking (MPPT). Shunt type and series type charge controllers are the simplest versions available in terms of structure in the market. In this type of charge controller, the relays open the circuit to stop charging when the voltage reaches a certain level. PWM charge controllers are switches that control power flow by changing the duty cycle [5]. MPPT charge controllers are defined as DC-DC converters allowing production of all needed power by the PV module [6]-[9]. Salman *et al*. [10] introduced an MPPT charge controller is designed using a DC-DC buck converter and a micro-controller. The proposed charge controller has been tested by a 200 w panel and a lead-acid battery. The simulation results show that the proposed charge controller improves system efficiency. Banaei and Bonab [11] developed a charge controller with a boost converter has been proposed. In the proposed charge controller, the inductor feature has been used to obtain the PV voltage at maximum power. Arunkumari *et al.* [12], presented the integration of SEPIC (single-ended primary inductor converter) converter and voltage Tripler structure is used to achieve an increase in static voltage for PV applications. The proposed model reduces switching and conduction losses. In terms of charge type, in references [13]-[15], the charge-up method of PV application has been discussed. The common charge-up methods of PV applications include constant current (CC), constant voltage (CV), constant current-constant voltage (CC-CV), and three-stage method. Layadi *et al.* [16] used a study has been performed on the effects of temperature in lead-acid batteries. The efficiency and increased battery temperature during the long-term charge in the sun are important points. The traditional CC and CV methods result in quick temperature rise [17].

In this paper, a PV charge controller using a DC-DC ZETA converter and P&O algorithm has been adapted for varying solar radiation conditions. On the other hand, in this paper, the lead-acid battery has been used as the energy storage. To prevent damage to the lead-acid battery, a novel three-stage charging method has been proposed in which the battery's charging voltage level is based on the battery temperature. The proposed charge controller is simulated in MATLAB/Simulink software.

2. METHOD

2.1. The proposed system

In this paper, designing of the MPPT solar charge controller is proposed using DC-DC ZETA converter and P&O algorithm. Furthermore, over-charging and gassing are phenomena that can reduce the battery life due to increase in battery temperature. To overcome this obstacle, the proposed novel three-stage charging method, which is the battery charging voltage levels are based on the battery temperature.

2.1.1. ZETA converter

Currently, different DC-DC converter topologies are present, and each converter has its limitations and topology [18]-[24], for instance, the CUK converter [25], the buck converter [10], the boost converter [11], and the SEPIC converter [12]. The ZETA converter is a transformer-type converter with a low-pass filter and its output voltage ripple is proportionally small [26]. Power is reduced by the ripple components, even with a low ripple amplitude, causing deviations from the MPP (maximum power point) [26]. Besides, as a result of the higher amount of ripple components, the filtering cost is increased and systems get larger and heavier. The researchers have been demonstrated that the ZETA converter has less output voltage and current ripple compared to other DC-DC converters [11], [26].

The basic ZETA converter circuit is shown in Figure 1. The circuit operation involves two phases. Firstly, it is initiated with the MOSFET connection and an off diode. In this phase, the current is drawn from the Vs inductors L1 and L2. In the second phase, it is initiated with off MOSFET and on diode. The whole stored energy in L2 is delivered to the load in this operation mode. The following relation is used for calculating the converter parameters [27]:

$$D = \frac{V_{out}}{V_{in}+V_{out}} \tag{1}$$

$$L_1 = L_2 = \frac{D\times V_{in}}{F_S\times \Delta I_L} \tag{2}$$

$$C_1 = \frac{D\times V_{out}}{F_S\times R\times \Delta V_C} \tag{3}$$

$$C_2 = \frac{D\times V_{in}}{8\times F_S^2\times L_2\times \Delta V} \tag{4}$$

$$\Delta I_L = \frac{D\times V_{in}}{F_S\times L} \tag{5}$$

$$\Delta V_C = \frac{D \times V_{in}}{8 \times F_S^2 \times C \times L} \quad (6)$$

where V_{out} shows the output voltage, V_{in} denotes the input voltage, F_s indicates the switching frequency, D represents duty cycle, ΔV_c denotes the voltage ripple, and ΔI_l is the current ripple.

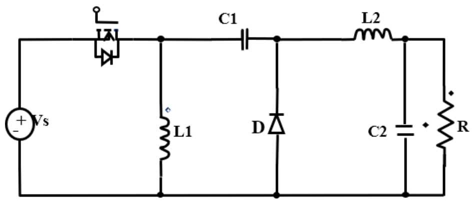

Figure 1. Circuit diagram of ZETA converter

2.1.2. The P&O algorithm

One of the most common algorithms in MPPT systems is the P&O algorithm because of its simple structure, requiring only two parameters (current and voltage), and accordingly, the output power is calculated. Its operating principle is based on perturbing, by a small rise in the array voltage and comparison between the array power and the previous perturbation cycle. The flowchart of the P&O approach is illustrated in Figure 2.

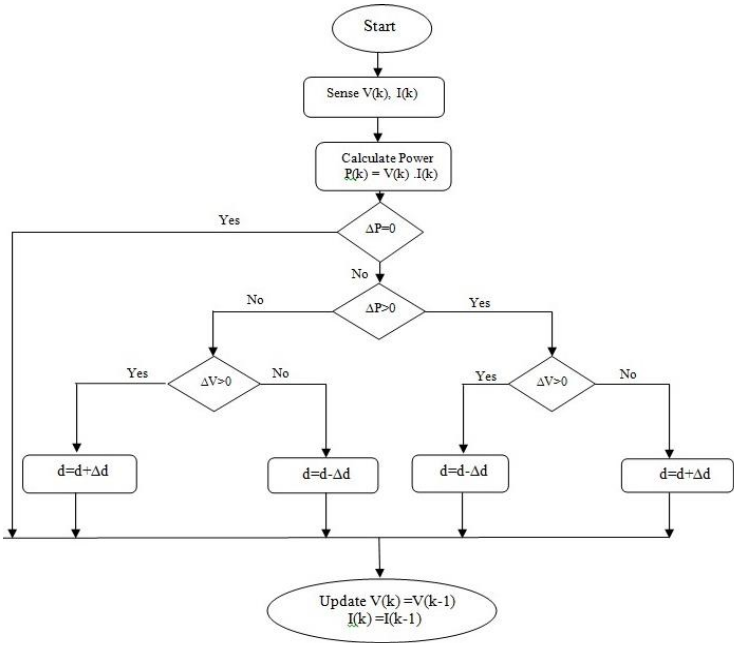

Figure 2. The flowchart of P&O algorithm

2.1.3. The traditional three-stage charging method

Three-stage charge-up method is widely used in lead-acid batteries. Figure 3 demonstrates the traditional three-stage charging method. The three stages to charge are bulk, absorption and float charges. In bulk stage, the charge controller provides a constant current and about 80% of the battery is charged. With reaching the battery voltage about 2.4 volts per cell, the current reduces and the charger voltage is maintained as constant. As mentioned earlier, adding more voltage than the pre-specified amount will damage the battery (gassing). In the third stage, the charger tries to maintain the fully charged battery. Since the value of the battery voltage threshold changes with temperature, the main drawback of this method is that the effect of changes in ambient temperature on determining the allowable voltage of the battery is not calculated. To overcome this obstacle, the proposed three-stage charging method, which is the battery charging voltage levels (bulk, absorption and float) are based on the battery temperature.

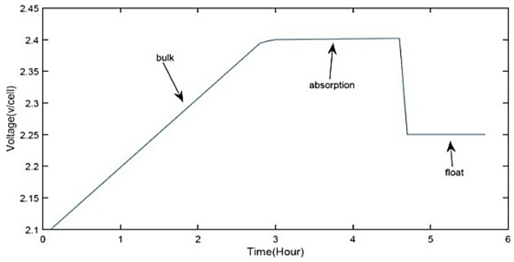

Figure 3. The traditional three-stage charging method

2.1.4. The proposed three-stage charging method

To prevent damages, caused by unsuitable charging voltages to the battery, this paper proposes a three-stage charging method in which the charging voltage level relies on battery temperature. More precisely, the bulk, absorption, and float voltage levels are calculated based on battery temperature. The three-stage voltage levels are computed as follows:

$$V_{Bulk} = (1.75.N_C) + (T - 25)N_C\beta \tag{7}$$

$$V_{Absorption} = (2.3.N_C) + (T - 25)N_C\beta \tag{8}$$

$$V_{Float} = (2.4.N_C) + (T - 25)N_C\beta \tag{9}$$

Where N_c=6 is the number of the cells of the lead-acid battery, β =-3.5 mv/℃/cell is the temperature coefficient (based on battery manufacturers), and T indicates the battery temperature. Figure 4 illustrates the proposed control algorithm for the three-stage charging method. The P&O algorithm is applied during the bulk charging stage and the battery is charged at 70-80% of the battery state of charge (SOC). The absorption is the second stage and the remaining 20-30% of the battery is charged in this stage. The third one is the float charging stage. The voltage reduces and a current of nearly less than 1% of the battery capacity is applied in this stage. This mode can be used to maintain a fully charged battery indefinitely.

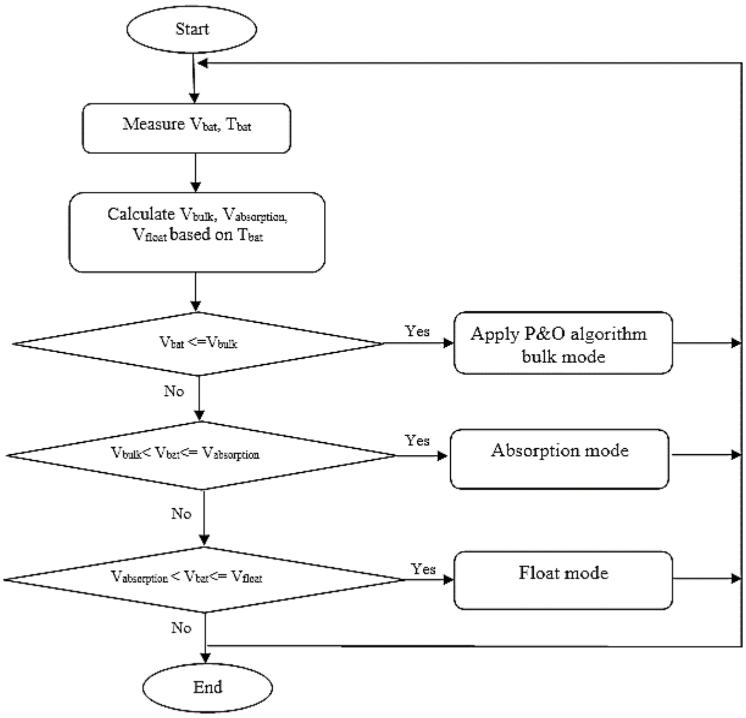

Figure 4. The proposed three-stage charging method

2.1.5. Battery temperature modeling

The lead-acid battery is the most widely used storage method for standalone PV system [4]. Battery temperature is one of the main causes of pressure in the battery that can affect its performance. The ambient temperature, charge and discharge rate, and the method of charging can have an effect on the battery temperature [16]. Battery operating temperature is calculated by:

$$T = Ta + \Delta T \tag{10}$$

where Ta and ΔT represent ambient temperature and temperature variations related to internal thermal, respectively. The expression of temperature variation ΔT is provided by:

$$\Delta T = R2_{int} \tag{11}$$

where R_{int} is the internal resistance versus the charge-discharge current, and has the following mathematical expression:

$$R_{\text{int}}(T) = \left(\frac{K_1}{1+I^{K_2}} + \frac{K_3}{(1+\frac{Q}{CT})^{K_4}} + K_5 \right)(1-\alpha_T) \tag{12}$$

where C_T and Q are the maximum battery capacity, the quantity of delivered or provided charges at time t, respectively. K_1 (0.042), K_2 (0.88), K_3 (0.033), K_4 (1.2), K_5 (0.0003), CT (15) and αT (0.02) are constants [16].

3. RESULTS AND DISCUSSION

In this paper, the MPPT charge controller using the DC-DC ZETA converter has been presented. In addition, to prevent damage to the battery, the novel three-stage charging method has been presented in which the battery's voltage level is based on the battery temperature. The standalone PV system has been simulated in MATLAB/Simulink software. In this study, the lead-acid battery 12 v, 50 Ah was used for simulation and the battery SOC was considered 30%. Figure 5 shows the overall standalone system. Table 1 shows the parameters value of the ZETA converter.

Table 1. The ZETA converter parameters

Parameters	Value
L1=L2	4 mH
C1	250 µF
C2	200 µF
Fs	10 kHz

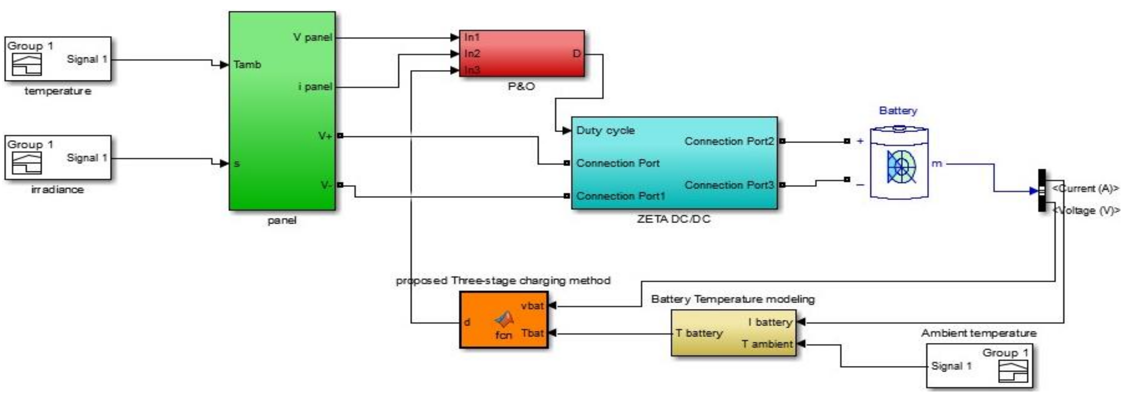

Figure 5. The overall diagram of the standalone PV system in Simulink

In order to better demonstrate the presented system's performance, we executed simulations in two case studies of temperature and radiation conditions as described in the following:

- Case study 1

In this case study, simulation results have been performed under fixed irradiation and temperature. The irradiation and temperature are considered at 800 W/m^2 and 30 ℃ respectively. This case study is considered a hot day and the initial battery temperature is assumed that 30 ℃. Figure 6 depicts the output power of the ZETA converter.

Based on simulation results, the proposed charge controller tracked 131.67 w (average of power tracking) of the maximum power. Figure 7 illustrates the comparison of the proposed three-stage and conventional three-stage charging methods. In the first hour, the battery will be charged at the bulk stage. The P&O algorithm is applied in this charging stage. In fact, in this stage, the maximum current is fed to the battery. In the next stage, the current decrease to safe levels as the battery becomes more fully charged to prevent over-heating and over-gassing. During this stage, any further charging at this voltage or higher can damage and reduce the battery life. In the proposed charging method, the charging voltage levels are based on the temperature. Given that the initial battery temperature is high, the charge mode enters the float stage sooner to prevent gassing and over-heating

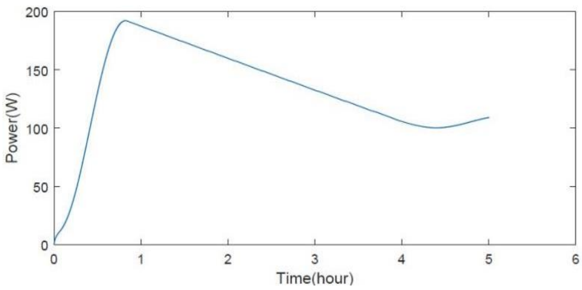

Figure 6. The output power of ZETA converter in case study 1

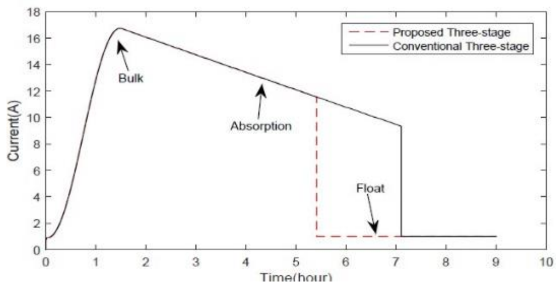

Figure 7. Comparison of the charging methods in case study 1

The average battery temperature is calculated using in (10). Table 2 shows the comparison of battery temperature during charging. The average battery temperature by the conventional method reaches 36.9 ℃ while it has reduced to 35.6 ℃. On the other hand, the reduction of battery life from heat is about 5% per each 1 ℃ [28]. The simulation results revealed that during battery charging with proposed method, the battery heats up less (1.3 ℃) during the charging stage and the proposed charging method can prevent a 6.5% reduction in battery life.

Table 2. Comparison of battery temperature during charging

Method	Average temperature
Conventional Three-stage method	36.9 ℃
Proposed method	35.6 ℃

- Case study 2

In this case study, simulation results have been performed under fixed irradiation and temperature. The irradiation and temperature are considered at 800 w/m^2 and 5 ℃respectively. This case study is considered a cold day and the initial battery temperature is assumed that 5 ℃. Figure 8 depicts the output power of the ZETA converter. The proposed charge controller tracked 148.72 w (average of power tracking) of the maximum power, which is an increase of 17.05 w compared to case study 1 (the amount has increased by 12%).

Figure 9 shows the comparison of the charging methods in this case study. Due to low initial battery temperature, in the proposed charging method, the battery enters the float stage later than the conventional three-stage method. Furthermore, with respect to the low initial battery temperature, the increase in the absorption stage does not damage the battery and consequently, the battery reaches full charge sooner (30 minutes) compared to the conventional three-stage method.

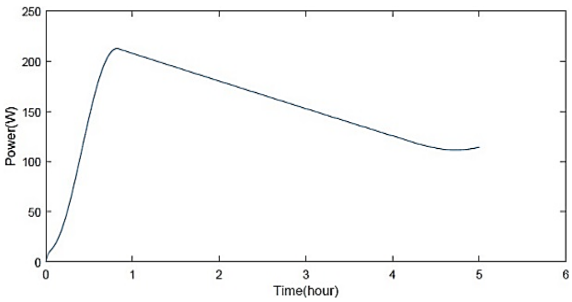

Figure 8. The output power of ZETA converter in case study 2

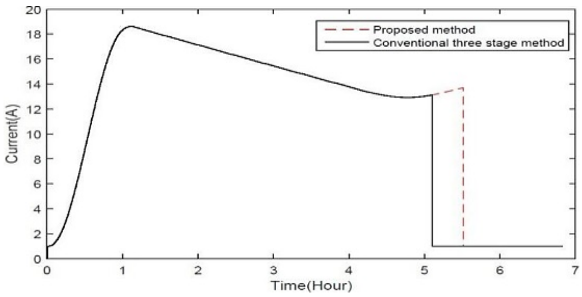

Figure 9. Comparison of charging method in case study 2

4. CONCLUSION

The charge controller is the heart of the standalone PV system that can increase system efficiency while reducing the overall system cost by preventing battery damage. Lead-acid batteries are extensively used in photovoltaic systems due to their availability and lower cost in comparison with the other types of batteries. High temperature, over-charging, gassing, and converter ripple cause severe harm to the battery and could reduce the battery lifetime.

In the present work, we proposed the MPPT charge controller using the DC-DC ZETA converter and P&O algorithm. The ZETA converter has less output voltage and current ripple compared to other DC-DC converters and reduces filtering costs. Furthermore, in this paper, the battery temperature model has been simulated. In addition, to prevent damage to the lead-acid battery, a novel three-stage charging method has been proposed in which the battery's charging voltage level is based on the battery temperature. In order to better demonstrate the presented system's performance, we executed simulations in two case studies (hot day and cold day). The simulation results demonstrated that the proposed MPPT charge controller can prevent a 6.5% reduction in battery life on a hot day. In addition, on a cold day, due to low initial battery temperature, in the proposed charging method, the battery enters the float stage later than the conventional three-stage charging method and the battery reaches full charge 30 minutes sooner. The proposed charge controller is simulated in MATLAB/Simulink software and the simulation results demonstrated that the proposed MPPT charge controller has a better performance compared to the conventional method.

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