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New effective PV battery charging algorithms

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ABSTRACT

Energy security and independence is one of the most growing concerns around the globe, combined with the environmental impact of traditional energy sources, renewable energy systems have become of great importance. Photovoltaic (PV) systems are the most popular form of renewable energy, as price have become reasonable, and deployment is scalable. However, in many schemes, PV systems require rechargeable batteries for energy storage, and increased system dependability. In this paper a numerical solution and two new control methodologies are proposed for effective battery charging from PV systems.

The first method is a modified single stage charge controller with a new maximum power point tracking (MPPT) algorithm. This method uses the battery voltage as a feed-forward term while optimizing the duty cycle of the converter to maximize the output power harvested from the PV cell.

The second method is a modified two stage charge controller. The proposed approach optimizes the duty cycle of the second converter, which includes maximum power passage and maximum current into the battery.

The main contribution of the proposed methods, is that the dynamic models of both the battery and the PV cell are taken into consideration, this greatly increases overall system efficiency.

1. Introduction

In standalone PV systems, the main objective is to charge a battery from PV modules under certain operating conditions, while protecting the battery from over voltage and over current. It is recommended that the battery be disconnect from the system when it is fully charged, and no load is connected (Hassoune et al., 2017). This is to protect the PV modules as well as the battery from heating, as the battery is fully charged and there is no current path.

PV charge controllers either use a single stage or two stages, depending on the complexity of the system. In single stage schemes, the mathematical model used does not take in consideration MPPT implementation to improve the overall system efficiency. For proper MPPT operation, both the energy source and the battery must be considered in the open loop solution. The main challenge here is that both the PV module and battery behavior are dynamic (Jackey, 2007).

In the two stage system, the first stage applies a MPPT algorithm, and the second stage charges the battery in one of many battery charging algorithms such as: Constant Current (CC), Constant Voltage (CV) or CC-CV to name a few (Swathika et al., 2013).

1.1. PV characteristics

MPPT algorithms are deployed to harvest the maximum available power from the PV (deBrito et al., 2013; Ngan et al., 2011). MPPT algorithms, which are implemented in the controller, regulate the duty cycle of the converter to maximize the power generated by the PV module by controlling the PV terminal voltage. The maximum power generated by the module, which occurs at the maximum power point (MPP), varies with the intensity of solar radiation and the surrounding temperature. Reaching this point is also dependent on the load, as it effects the PV voltage (Reisi et al., 2013; Bendib et al., 2015). In addition, the I-V characteristic of the PV module mainly depend on the intensity of solar radiation and the surrounding temperature of the module (Reisi et al., 2013). All these characteristics are dynamic in nature. The developed model, uses characteristic equations of the PV to determine the MPP.

1.2. MPPT algorithms and PV charging systems

Over the past decade several MPPT algorithms have been researched and developed. For example Reisi et al. (2013) developed various MPPT methods, which range from using the open circuit voltage method to the more complex perturbation and observation

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methods. Ferdous et al. (2012) utilized feedback from the solar cell to design an open voltage MPPT. Rezk and Eltamaly (2015) compared different MPPT techniques proposed in literature. Brea et al. (2010) proposed using feedback from the solar module to track the maximum power point. Swathika et al. (2013) developed a fuzzy logic control system based on feedback from the battery. Chiang et al. (2009) proposed implementing a PV charge controller with a SEPIC converter. Manju et al. (2011) presented a charge controller with a single stage DC-DC converter. The proposed system's feedback depends either on MPPT or battery charge, but not at the same time. Kanakasabapathy et al. (2015) designed a charge controller for either the MPPT or the battery charging. Shreelakshmi et al. (2013) proposed a bi-directional DC-DC converter to charge the battery from a PV module and using the battery when the PV module is not available. Yau et al. (2012) developed a PV charging system with a two stage DC-DC converter to maximize the power from the PV module and to control the battery charging based on constant voltage only. El Khateb et al. (2013) proposed a cascaded DC-DC converter for the charge controller. The first converter is to maximize the power produced by the PV module while the second converter controls the battery charging with two stages, constant current and constant voltage modes. Debnath and Chatterjee (2015) developed a two stage charge controller to improve the MPPT and to protect the battery from overcharging/discharging and to connect the system to the grid. Caracas et al. (2015) proposed an optimized charging system, based on MPPT, but no battery dynamics. Kinjal et al. (2015) discussed the method for maximum power point for PV modules, and compared two method for MPPT include that perturb and observe and incremental conductance. Yilmaz et al. (2017) discussed a PI controlled Flyback controller under different environmental conditions, but not battery dynamics. Lineykin et al. (2012) presented a mathematical model for the PV cell and used the parameters for the equations from the PV cell's date sheet. Deveci and Kasnakoğlu (2016) proposed a numerical modeling and simulation technique to improve the performance of theoretically designed stand-alone photovoltaic (PV) systems. Horkos et al. (2015) discussed and compared different charging techniques for lead acid batteries. The author has summarized these charging techniques and the advantages and disadvantages of each method, which serves as a useful guide in choosing the right charging method for a system. None of the previous research considered both the PV and the battery dynamic nature in the controller design at the same time.

2. Developed model

From the current-voltage (I-V) and the power-voltage (P-V) characteristic of the PV, the following characteristic equation can be derived for the equivalent circuit in Fig. 1 (Geethalakshmi et al., 2014):

$$I_{PV} = I_{ph} - I_0\left(\exp\left(\frac{V_{pv} + (I_{pv}R_s)}{nV_t}\right) - 1\right) - \left(\frac{V_{pv} + IR_s}{R_{sh}}\right) \tag{1}$$

$$P_{pv} = \left(I_{ph} - I_0\left(\exp\left(\frac{V_{pv} + (I_{pv}R_s)}{nV_t}\right) - 1\right) - \left(\frac{V_{pv} + IR_s}{R_{sh}}\right)\right)(V_{pv}) \tag{2}$$

where I_{PV} = output current (A); I_{ph} = Photocurrent; I_0 = reverse saturation current (A); V_{pv} = voltage across the PV cell (V); V_t = thermal voltage; n = diode ideality factor (1–2); R_s = series resistor of PV cell and R_{sh} = parallel resistor of PV cell; P_{pv} = PV power.

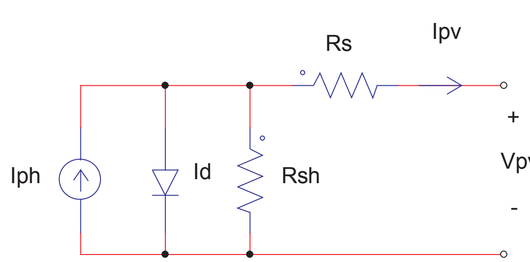

Fig. 1. PV model.

Peng's (2011) derived characteristic equations for a lead-acid battery from both simulation and experimental results. The voltage drop across R_s and R_t in the dynamic response model can be described by Eq. (3):

$$V_{drop} = IR_s + IR_t\left(1 - e^{-\frac{t}{R_t C_t}}\right) - V_c e^{-\frac{t}{R_t C_t}} \tag{3}$$

where V_{drop} = voltage dropped across R_s and R_t; V_c = the voltage across the capacitor; I = the current in the battery; R_t = Resistor of battery; C_t = battery capacitance; V_s = voltage source.and

$$V_{bat} = E_m + IR_2 + IR_1\left(1 - e^{-\frac{t}{R_1 C_1}}\right) - V_c e^{-\frac{t}{R_1 C_1}} \tag{4}$$

where E_m = initial battery voltage; R_1 = variable battery resistance; R_2 = constant battery resistance; C_1 = battery equivalent capacitance; I = current in battery; t = time;

The SEPIC converter's transfer function is as following:

$$\frac{V_o}{V_i} = \frac{d}{1-d} \tag{5}$$

where Vo = output voltage of converter; Vi = input voltage of converter; d = duty cycle of converter.

Now, system equation for the proposed equation in Fig. 2 can be derived as following:

$$\frac{\partial P}{\partial V} = (G \times I_{SC}) - I_0\left(\exp\left(\frac{V_{pv} + (I_{pv}R_s)}{nV_t}\right) - 1\right) - \left(\frac{V_{pv} + IR_s}{R_{sh}}\right) - \left(V_{pv} \times I_0 \times nV_t \times \exp\left(\frac{V_{pv} + (I_{pv}R_s)}{nV_t}\right)\right) \tag{6}$$

where G = light intensity, I_{SC} = PV short circuit current.

$$P_{bat} = \eta \times P_{pv} \tag{7}$$

where η = Efficiency of converter.

$$d = \frac{V_{bat}}{V_{bat} + pv} \tag{8}$$

where d = duty cycle for the converter; V_{bat} = battery voltage; V_{pv} = PV module voltage and V_D = voltage on the diode in converter.

3. Numerical model

Fig. 2 shows the block diagram of the proposed solution. Following the flow chart in Fig. 3, demonstrates how the optimal duty cycle for the converter is obtained.

First the system reads the state of charge of the battery and the light intensity of the PV module. Then the maximum power for PV module is

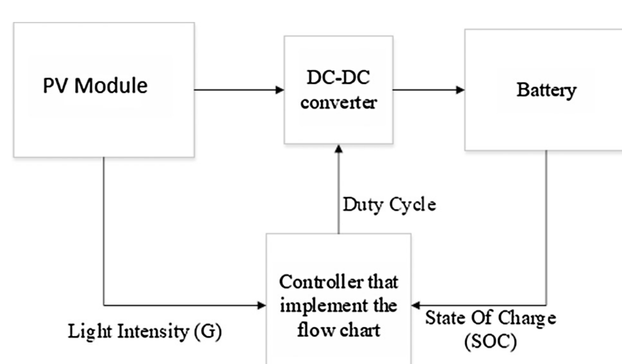

Fig. 2. Proposed system for numerical solution.