Integrated Solar Controller for Solar Powered Off-grid Lighting System

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Abstract

An integrated solar controller for off-grid lighting system is proposed to synthesize battery charger and light emitting diode (LED) driver with the benefit of simplified system architecture and reduced system cost. Based on bi-directional converter (BDC) with Sepic and Zeta topologies, high efficient solar energy collection is realized by maximum power point tracking (MPPT) method via battery parameter, and constant current driving for LED module is implemented by digital hysteresis control strategy. Theoretical analysis and experiment results are presented to verify the validity and feasibility of the proposed control.

Keywords: Photovoltaic (PV), Maximum power point tracking (MPPT), Controller, Light emitting diode (LED), Bi-directional converter (BDC)

Introduction

Solar photovoltaic (PV) panel by converting solar radiation into DC electricity using semiconductors that exhibit the photovoltaic effect is suitable for small-scale solar application system because of its implementation flexibility. The output power of solar panel depends on solar insolation level and PV module temperature, as well as load property. The control method of maximum power point tracking (MPPT) enables the solar charge controller to track the MPP under any input and output conditions.

Many MPPT methods have been developed and implemented. The methods vary in complexity, sensors required, convergence speed, cost, implementation hardware, range of effectiveness, popularity, and in other respects [1]-[3].

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Light emitting diodes (LEDs) have been widely used in many products such as liquid crystal display (LCD) panel backlighting [4] and street lighting [5]. The significant improvements achieved for high-power or high-brightness LEDs are gradually realizing the possibility of replacing conventional light sources based on heated filaments and gas discharges with high-power LEDs [6]. The emission intensity of LEDs varies linearly with the forward current for small currents, but it shows a tendency to saturate at high currents. This phenomenon implies that the efficacy of an LED is lower if operated at high forward currents [7]. Two commonly used driving techniques for LEDs employ DC and PWM current driving with their inherent advantages and disadvantages [8].

As a typical solar powered off-grid application, lighting system converts electricity generated by solar panel to light load. In conventional solar lighting system, charger and driver are independent controllers and responsible for energy collection and energy utilization by interacting with battery. Many solar powered off-grid lighting systems have the feature of time-separate energy harvest stage and energy utilization stage e.g. solar street lamp and solar landscape lights. In these applications, single solar controller integrating battery charging and discharging functions is attractive because it makes full use of converter hardware and simplifies system configuration.

An integrated solar controller for off-grid lighting system is proposed. Based on Sepic-type bi-directional converter (BDC), both battery charging and LED driving are realized with improved flexibility of voltage level matching among solar PV panel, battery, and LED module. A modified perturb & observe (P&O) MPPT control via battery parameters is proposed and implemented to improve control performance with reduced implementation cost [9]. Digital hysteresis constant current control for driving LED module is also analyzed and verified by experiments.

**System Architecture Optimization**

Typical solar off-grid lighting system consists of solar panel, solar charge controller, battery, and light source. Optimized system architecture brings benefit to customer with decreased cost, improved reliability, and enhanced flexibility.

Based on BDC, the system architecture of solar powered off-grid lighting is shown in Fig. 1. During daytime when solar irradiance is available, PV panel charges battery through diode \( D_{PV} \) and BDC with battery switch \( S_{bat} \) closed and LED switch \( S_{LED} \) open. Power flows from PV panel to battery. During nighttime when sunlight is not available and light is needed, PV panel doesn’t work, and battery supplies energy to LED module through LED switch \( S_{LED} \) with battery switch \( S_{bat} \) closed. Power flows from battery to LED module.

Improved flexibility will be obtained by changing the stepping-up or stepping-down topology with BDC such as Sepic topology which has both stepping-up and stepping-down functions. Solar off-grid lighting system based on Sepic-type BDC is shown in Fig. 2, in which battery switch and LED switch are
Battery Charging by Novel MPPT Method

Perturb and observe (P&O) MPPT method is adopted for its important advantages as simplicity and applicability to almost any PV system configuration. Conventional P&O technique requires to sense PV panel output voltage and output current for MPPT implementation.

In off-grid solar system with battery as energy storage, the charging current and battery need to be monitored to realize charging control. By taking the PV panel and the MPPT converter as an integrated energy source, the MPPT algorithm could be implemented from the battery side to obtain the maximum charging power without the information of PV panel. Less sensing circuitry contributes to decrease the complexity and cost of the MPPT controller in off-grid solar applications.

The MPPT control method based on load parameters have proved the feasibility of the P&O MPPT implementation via load parameters. However, the optimization of transient MPPT behaviour has not been covered by these literatures [10]-[12].

In practical off-grid solar applications, the control objective is to maximize the power/energy flow delivered to the load, e.g. energy storage. From this point of view, it is reasonable to choose load power instead of PV power as control variable and to estimate output power of PV panel by battery charging power. Analysis shows that the mathematical expression of typical single switch DC/DC converter suitable for solar charge controller is monotonous regarding duty cycle. In this way, it is possible to judge the operating point location without the information of PV panel. Improved P&O MPPT algorithm based on load parameter is implemented with the control flow chart in [9].

Both the continuous current mode (CCM) and the discontinuous current mode (DCM) of Sepic converter are studied, in which the definition of DCM is the sum of both inductors current has the duration of being zero. Solar charge controller based on Sepic topology is shown in Fig. 3, where the port connected with inductor L_a and power switch Q_b are defined as port a and port b respectively, \( V_a \) and \( V_b \) represent output voltage of PV panel and battery voltage, and \( C_c \) is coupling capacitor. There are two operating modes in CCM and three modes in DCM, respectively. In CCM, by applying voltage-second balance principle for \( L_a \) and \( L_b \),

\[
V_a D_{Qa} T_s + (V_a - V_{Cc} - V_b) (1 - D_{Qa}) T_s = 0, \\
(1)
\]

\[
V_{Cc} D_{Qa} T_s + (-V_b) (1 - D_{Qa}) T_s = 0,
\]
(2) where $D_{Qa}$ is duty cycle of $Q_a$.

$$\frac{V_b}{V_a} = \frac{D_{Qa}}{1-D_{Qa}}$$

(3)

$$V_{Cc} = V_a$$

(4)

By replacing $V_a$ with $V_{PV}$ and $V_b$ with $V_{bat}$ in (3),

$$\frac{V_{bat}}{V_{PV}} = \frac{D_{Qa}}{1-D_{Qa}}.$$  

(5)

For mode 3 in DCM, $Q_a$ is disabled while $Q_b$ is enabled, but no current flows through $Q_b$. The average power is determined by

$$P_a = P_b = \frac{D_{Qa}^2 V_a^2}{2 f_s} \left( \frac{1}{L_a} + \frac{1}{L_b} \right).$$

(6)

By replacing $V_a$ with $V_{PV}$, $V_b$ with $V_{bat}$, and $P_b$ with $P_{bat}$,

$$P_{bat} = \frac{D_{Qa}^2}{2 f_s} \left( \frac{1}{L_a} + \frac{1}{L_b} \right) V_{PV}^2.$$  

(7)

The intersection of the parabola expressed by (7) and the P-V characteristic curve of PV panel determine the operating point in DCM. Because $V_{bat}$ rises very slowly, the parabola shows the monotonicity between $V_{PV}$ and $D_{Qa}$ in DCM. As for CCM, $V_{PV}$ is inversely proportional to $D_{Qa}$. For the whole duty cycle range, the larger the $D_{Qa}$ is, the smaller the $V_{PV}$ will be. This phenomenon proves that it is applicable to judge $V_{PV}$ variation direction by means of comparing the $D_{Qa}$’s of two adjacent control intervals.

The key waveforms of Sepic-based charger are shown in Fig. 4. The profile of $V_{Cc}$ is almost the same as that of $V_{PV}$. As for their mean value, $V_{Cc}$ is about 0.5 V lower than $V_{PV}$ due to the forward voltage drop of schottky diode $D_{PV}$ in Fig. 3. The level of $V_{bat}$ during the time interval of $Q_a$ off or $Q_b$ on is higher than that of $Q_a$ on or $Q_b$ off.

![Diagram](image-url)
The MPPT performance of Sepic-based solar charge controller is measured in the experimental setup, in which the energy source is a solar array simulator (SAS), and the data acquisition system (DAS) records the input and output data of the solar charge controller. The target solar panel is the STP070D-12/SEA from Suntech. The MPPT efficiency of the Sepic-based charger is calculated in terms of [13] with the data sensed by the DAS. The static MPPT testing results are shown in Table 1, where the testing conditions include solar cell temperature and solar irradiance level. The dynamic testing data is at the same level as that of the static one, verifying the validity and feasibility of the MPPT control.

Table 1: Static MPPT performance of Sepic-based charger

<table>
<thead>
<tr>
<th>Conditions</th>
<th>10 ºC &amp; 200 W/m²</th>
<th>10 ºC &amp; 600 W/m²</th>
<th>45 ºC &amp; 200 W/m²</th>
<th>45 ºC &amp; 600 W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPPT efficiency</td>
<td>94.9%</td>
<td>97.4%</td>
<td>94.7%</td>
<td>97.0%</td>
</tr>
</tbody>
</table>

**LED Driving Based on Digital Hysteresis Control**

When power flows from battery to LED module, the circuit in Fig. 2 is actually a Zeta topology, with the schematic diagram re-drawn in Fig.5. The operating principle analysis of Zeta converter is similar to that of Sepic converter in Section III, with two operating modes in CCM and three modes in DCM. The definition of DCM and CCM in Zeta converter is whether the sum of inductor a current $i_{La}$ and inductor b current $i_{Lb}$ has the possibility of being zero.

By applying voltage-second balance principle for $L_a$ and $L_b$ in CCM,

$$V_a = \frac{D_{Qb}}{1 - D_{Qb}} V_b,$$

(8)

$$V_{Cc} = V_a,$$

(9)

where $D_{Qb}$ is duty cycle of $Q_b$.

For mode 3 in DCM, $Q_b$ is disabled while $Q_a$ is enabled, but no current flows through $Q_a$. The average power is given by

$$P_b = P_a = \frac{D_{Qb}^2 V_b^2}{2 f_s} \left( \frac{1}{L_b} + \frac{1}{L_a} \right),$$

(10)
The system setup based on Zeta topology is shown in Fig. 6 (a), where lead acid battery specification is 12 V 100 Ah, and LED module consists of 15 pieces of Philips Lumileds Luxeon LXK2-PB12-L00. The prototype of LED driver shares the same controller as that of solar charger shown in Fig. 6 (b), where the SAS charges the same battery through Sepic-based charger circuit.

The LED driver in Fig. 6 (a) works at constant current control mode. In conventional implementation of constant current driving, the practical LED driving current is sensed and compared with the current reference, and the error signal is processed by a proportional and integral (PI) type current regulator. In Zeta-based driver, another type of current regulator is studied and implemented based on digital hysteresis control, as is shown in Fig. 7, where $I_{LED}$ is practical driving current of LED module, $I_{set}$ is current reference, $\Delta I_{th1}$ is threshold of current adjustment, and $\Delta I_{th2}$ is larger threshold that $\Delta I_{th1}$ for determining the perturbation steps ($\Delta D_2 > \Delta D_1$) of $D_{Qb}$.

![LED driver](a), ![Solar charger](b)

**Fig. 6. Sepic-Zeta based BDC**

![Control flow chart](chart)

**Fig. 7. Control flow chart of proposed digital hysteresis constant current control**

The analysis of the two LED driving techniques shows that the proposed one has the merits of lower control processor requirements because no multiplication operation is needed to implement the constant driving control. The conventional PI method has the advantage of errorless control in theory.

The experimental results of Zeta-based LED driver with constant current control implementation shown by Fig. 7 are presented in Fig. 8, where $V_{LED}$ is terminal voltage of LED module. The setting point of current reference is 350 mA.
In Fig. 8 (a), the mean value of $I_{\text{LED}}$ is very approximate to the current reference, showing the validity of proposed control. When the power switch $Q_b$ is turned off, lead acid battery is in the empty load state, and its terminal voltage will rise comparing to battery voltage with load according to the properties of lead acid battery. In Fig. 8 (b), $I_{\text{LED}}$ fluctuates around the setting point of 350 mA. The ripple component of $I_{\text{LED}}$ could be further suppressed by fine-tuning control parameters in Fig. 7.

**Conclusion**

An integrated solar controller synthesizing both battery charging and LED driving functions for off-grid lighting system is proposed. The BDC for the integrated solar controller with Sepic and Zeta modes improves the control flexibility of voltage level matching among solar PV panel, battery, and LED module. Analysis shows that there is always a monotonic relationship between the operating voltage of PV panel and duty cycle of power switch regardless of inductor current continuous or discontinuous modes. Either static or dynamic MPPT efficiency of the integrated solar controller in charging mode is quite good. The digital hysteresis constant control of the integrated solar controller in driving mode is proposed and verified by experimental results.

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**References**


