A Modular Self-Controlled Photovoltaic Charger with Inter-Integrated Circuit (I²C) Interface

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Abstract—This paper presents a modular self-controlled photovoltaic (PV) charger with maximum power point (MPP) tracking and pulse-charging schemes. The studied PV modules can be flexibly parallel-connected through interleaved operation using an Inter-Integrated Circuit (I²C) interface. The MPPT control of PV panel is implemented by using a current-sensing technique with the on-state resistance $R_{\text{ds(on)}}$ of the power switch. An expensive hall-effect sensor and additional current-sensing resistor are both not needed. A pulse-charging scheme without extra battery-current sensor is also designed to prolong the lifetime of the acid-lead battery. The operation principles and design considerations of the proposed PV charger are analyzed and discussed. A laboratory prototype is implemented and tested to verify its feasibility.

Index Terms—Self-Controlled PV Charger, Maximum Power Point Tracking, Pulse-Charging, I²C Interface, Interleaved Operation

I. INTRODUCTION

The continuous growth of the global energy demand associated with the increasing concern with environmental issues has brought about great interest and development in renewable energy sources such as photovoltaic (PV) technology [1,2]. Typically, several PV panels are connected in series to provide high-voltage output. These PV strings can then be parallel-connected for high-power applications. However, the PV panels often work in mismatching conditions due to different panel orientations and shadowing effects. This mismatching problem thus reduces the power production of the whole PV string. To overcome the drawback, several literatures have proposed a module integrated converter (MIC) concept [3-6]. The individual MPP tracking modules are attached to each PV panel for extracting its maximum power. As shown in Figure 1(a), such a PV module composed of a PV panel with an individual DC/DC converter is called self-controlled PV module (SCPVM). The DC/DC converter is combined with a digital controller to implement the MPP tracking and battery charging functions.

For the MIC mounted on a PV panel, a long useful lifetime and low power dissipation must be ensured. Thus, the commercial success of a SCPVM highly depends on its reliability and efficiency. This is challenging because the SCPVM is cyclically exposed to a high-temperature environment under solar irradiation [7,8]. In addition, electrolytic capacitors (ECs) are often used in MICs. Their short lifetime always deteriorates the reliability of the SCPVM system. In this paper, we study a modular PV charger for the multi-phase SCPVM configuration shown in Figure 1(b). The PV chargers can be flexibly parallel-connected through interleaved operation. Ripple current cancellations can thus be achieved for the elimination of ECs. An Inter-Integrated Circuit (I²C) interface is developed to realize the interleaved operation among the PV chargers. There are many communication interfaces, e.g. SPI or CAN that can be applied for realizing a master-slave system. SPI is not suitable for multi-slave applications. CAN is good for long-distance communications. However, it is relatively complicate compared with I²C for the studied MIC application. The I²C is a half-duplex, synchronous protocol developed by Philips Semiconductors. It can use only two signal wires to implement an addressable communication between the master and slave modules [9,10]. Moreover, the MPPT control of PV panel is realized by using a $R_{\text{ds(on)}}$ current-sensing technique. An additional current-sensor is not needed. Thus, extra resistive current-sensing losses can be eliminated. This is useful for raising conversion efficiency and circuit miniaturization. In recent research literatures, some other methods for current sensorless PV chargers have been published [11,12]. In [11], the authors presented a simple current sensorless MPPT control method. By using the DC resistance (DCR) of input inductor, the PV current information can be obtained and a high MPPT accuracy can be achieved. However, a large inductor may be necessary for the DCR current-sensing method according the design consideration of minimum inductance. For the photo of a prototype circuit in [11], a 7.5mH inductor was used. It will be not easy to realize circuit miniaturization. In [12], the authors presented a current sensorless MPPT method for the interleaved dual boost (IDB) converter. The use of an IDB converter reduces the PV current ripple. However, according to the experimental waveforms shown in [12], the measured MPPT accuracy is less than 90%. In addition, the studied MPPT method is not suitable for a single boost converter according to the theoretical analysis.
For the conventional continuous-current (CC) charging method, ions are generated at one electrode during charging period and must move to the other electrode. An ion concentration gradient builds up due to mass transport limitations within the battery. This results in poor charging efficiency which leads to heat generation, poorer battery capacity and shorter lifetime. In this paper, a pulse-charging scheme without extra battery-current sensor is also designed to prolong the lifetime of the acid-lead battery.

II. SYSTEM DESCRIPTION

For description convenience, Figure 2(a) shows a two-phase master and slave PV chargers. This charger consists of two boost DC/DC converters with individual digital controller. The control block diagrams for the master and slave modules are shown in Figures 2(b) and 2(c), respectively. The PV voltage $V_{pv}$ and PV current $I_{pv}$ are sensed by the master module controller in Figure 2(b) to realize the maximum power point tracking (MPPT). The pulse-width of battery current $I_b$ is also determined by sensing battery voltage $V_b$ to prevent overcharging the battery bank. An I2C interface is developed for achieving the modules’ communication. As shown in Figure 2(c), a phase-shift control is built in the slave module to realize the interleaved operation. For the two-phase configuration in Figure 2, the phase-shift amount $\alpha$ is 180°.

Figure 3(a) shows the block diagram of I2C interface, in which the Serial Data (SDA) and Serial Clock (SCL) are data-transfer line and clock line, respectively. By using the SDA and SCL, the communication between the master and slave modules can be achieved. The interleaved operation can be then realized. Figure 3(b) is the 7-bit I2C addressing scheme used in this paper. S is the start condition; R/W is a reading/writing bit; ACK is the acknowledgment bit inserted in data bits; and P is the stop condition. The duty ratio for power switches is calculated by master module controller and is then sent to slave module via the developed I2C interface. Addressing and communication can be achieved by the used 7-bit addressing scheme to realize the studied interleaved operation.
For conventional MPPT implementation for high-power applications, a hall-effect sensor with good linearity and high reliability characteristic is often used to sense the PV panel current [13]. However, the hall-effect current-sensing technique is too expensive and huge for practical MIC applications. A current-sensing technique using current-sensing resistor is suitable for low-power applications. Low cost and good frequency-response features are its main advantages [14-16]. However, the extra resistive losses will result in undesired thermal problem. In this paper, a $R_{ds(on)}$ current-sensing technique is used to implement MPPT function for the studied PV charger. As shown in Figure 4, the on-state drain-source voltage $V_{ds(on)}$ of the master module switch Q1 is sensed via a small sample-transistor Qs. A 3.3V zener diode Zc is added to protect the ADC pin of digital controller. For a two-phase PV charger shown in Figure 2(a), the $V_{ds(on)}$ can be used to represent the PV array current $I_{pv}$ as follows:

$$V_{ds(on)} = \frac{I_{pv}}{2} R_{ds(on)}$$

Therefore, additional current-sensor is not needed, and extra resistive current-sensing losses can be eliminated. Some parameters including conversion efficiency $\eta_{con}$, MPPT accuracy $\eta_{mppt}$, and overall efficiency $\eta_{overall}$ are often used to evaluate the performance of a PV MIC.

$$\eta_{overall} = \eta_{con} \times \eta_{mppt}$$

$$\eta_{con} = \frac{P_o}{P_{pv}}$$

$$\eta_{mppt} = \frac{P_{pv}}{P_{pv,m}}$$

where $P_o$ denotes the output power of the PV MIC. $P_{pv,m}$ and $P_{pv}$ represent the maximum power and practical output power of the PV panel.

MPPT control is maintained during the charging period $T_p$ while electrolyte reaction of battery is relaxed during the rest period $T_r$. By allowing the ion concentration to return to normal levels on a routine basis, the battery lifetime can be prolonged. The pulse width of battery charging current is determined by battery voltage $V_b$. When the battery voltage $V_b$ reaches to $V_{b,5}$, a pulse current with a fixed narrow width is sent to float-charge the battery.

![Figure 4 Rds(on) Current-Sensing Circuit.](image)

For conventional battery charger applications, a CC/CV charging scheme shown in Figure 5(a) is often adopted for prolonging the battery lifetime [17-21]. A CC charging scheme is firstly adopted to avoid the occurrence of over-current problem due to low battery voltage. As the battery voltage rises to a preset voltage $V_{b,cv}$, a CV charging scheme is used to prevent overcharging problem. For the conventional battery charging scheme, an expensive battery current-sensor is also necessary for CC charging implementation. MPPT operation must be disabled to avoid overcharging problem during the CV charging period. In this paper, we implement a pulse-charging scheme without extra battery-current sensor for the studied SCPVM applications. As shown in Figure 5(b), the MPPT charging proceeds first. When the battery voltage rises to $V_{b,set}$, a pulse-charging current is sent to battery.

![Figure 5(a) CC/CV Charging and (b) Pulse-Charging Schemes.](image)

### III. DESIGN CONSIDERATIONS

In this paper, a DSP chip TMS320F2808 is adopted to realize the digital controller of the studied PV charger. The design considerations of the studied I2C interface and battery charging scheme will be described and discussed as follows.

#### A. I2C interface

As mentioned above, the interleaved operation of the studied PV charger is achieved by using the I2C communication. Figure 6 shows a flow chart of the developed I2C interface. The detailed control flow is described as follows.

1) After system initialization, the PWM synchronization operation between the master and slave modules is completed. The I2C communication mode then starts.
2) The master module sends the Start-bit (S) to the I2C bus. As the slave module receives the S signal, master module starts the addressing operation. Otherwise, the master module re-sends the S signal to the I2C bus if the slave module misses it.
3) During the addressing operation, the master module sends a 7-bit address to the I2C bus and waits the ACK signal. As the ACK response is sent back, the master module continues to send a lower 8-bit data (Lo) to the I2C bus and
wait the corresponding ACK signal from slave module.

5) As the slave module completes the data reception, a Stop (P) signal is sent to the I²C bus. The system then comes to the stop state and then goes back to the initialization state.

Figure 6 Flow Chart of the I²C Interface.

Figure 7(a) shows the studied synchronous connection configuration. EPWMSYNCI and EPWMSYNCO are respectively the input and output synchronous pins of TMS320F280. By connecting the EPWMSYNCO pin of master controller and the EPWMSYNCI pin of slave controller, the PWM synchronization operation between the master and slave modules can be achieved. Figure 7(b) shows the PWM synchronous waveforms. At the time point $T_{m\_zero}$, the master epwm counter is zero. EPWMSYNCO pin outputs a synchronous pulse signal SYNC_P that resets the slave epwm counter by EPWMSYNCI pin. The phase shift $T_{phs}$ calculated by the master controller is then sent the slave controller via I²C interface. When the slave epwm counter reaches $T_{phs}$, it will be reset. In this work, a ring-type connection configuration is used for module communication among the parallel PV chargers. Figure 7(c) shows the interleaved waveforms among three modules. The master module firstly sends a signal on the ring bus to get the module number information. The clock signal is then produced and sent to the slave modules that duplicates and delays the clock signal to get their own PWM signals. Interleaved operation of the studied PV chargers can be achieved by the simple communication architecture design.

B. Battery pulse-charging design

Figure 8 shows the flow chart of the studied pulse-charging design. This type of charging scheme is commonly known as “on-off charging” or “intermittent charging” [22-24]. By allowing the ion concentration to return to normal levels on a routine basis, the battery lifetime can be prolonged [25-29]. In this study, MPP tracking is retained during the charging period to raise the utility of PV array while the electrolyte reaction is relaxed during the rest period to prolong the battery lifetime. The P&O MPPT method usually reacts slowly. For the studied battery charging scheme, the instantaneous PV power and duty cycle of the power switch at the end of the previous charging period are recorded and applied to the beginning of the next charging period. Thus, a fast MPPT tracking with high accuracy can be achieved during a narrow charging period. The detailed control flow is described as follows.

1) As the battery voltage less than the preset voltage level $V_{b\_set}$, the PC flag is set at “0” and the pulse-charging function is disabled. The MPPT charging is maintained to extract the maximum output power of PV panel. We adopted a Perturb and Observe (P&O) method, which has the advantages of simplicity and good performance [2].

2) When the battery voltage reaches $V_{b\_set}$, the PC flag is set at “1” and the pulse-charging function is enabled. The charge-period $T_c$ and the rest-period $T_r$ in the pulse-period $T_p$ are determined by the sensed battery voltage $V_b$ as follows:

$$T_c[k] = T_c[k-1] - \left[ \left( \frac{V_{b\_f} - V_b[k-1]}{V_{b\_f} - V_{b\_set}} \right) \times 0.9T_p \right]$$

$$T_r = T_p - T_c$$

where $T_c[k]$ and $T_c[k-1]$ are the charge-periods at the sampled time k and k-1, respectively; $V_{b\_f}$ is the float-charging voltage;
As the charge-period counter $P_{\text{count}}$ less than the calculated charge-period $T_c$, it will be accumulated to maintain the MPP tracking. When the $P_{\text{count}}$ reaches to $T_c$, the rest period counter $R_{\text{count}}$ begins accumulating. The PWM signal is disabled until the counter $R_{\text{count}}$ equals to $T_r$. During the rest period $T_r$, battery electrolyte reaction is relaxed to prolong battery lifetime. As the rest period is ended, the counters $P_{\text{count}}$ and $R_{\text{count}}$ are both reset. The charge-period $T_c$ and rest-period $T_r$ are then recalculated.

4) As the battery voltage $V_b$ higher than the preset float-charging voltage $V_b,f$, the pulse-width of charging current is set as a fixed narrow charge-period $T_c,f$. The float-charging period will then be terminated as the battery voltage reaches the preset overcharge level $V_{oc}$. This work aims to study a PV charger for MIC applications. Simplicity and low cost are the major design concerns. For the considerations of system cost, circuit miniaturization and overall efficiency, the studied $R_{\text{ds(on)}}$ current-sensing technique has good performance for maximum power point tracking. Anyway, the temperature compensation schemes presented in [34, 35] also can be applied for the studied photovoltaic charger to increase battery lifetime and reduce the affection of current sensing errors if necessary. Battery manufacturers usually provide temperature schemes. The temperature compensated battery charger adjusts the float charging voltage based on the sensed ambient temperature or battery temperature to avoid overcharging.

IV. EXPERIMENTAL VERIFICATIONS

Table 1 shows the circuit parameters of the laboratory prototype. A series of experimental tests have been carried out to verify the feasibility of the studied modular PV charger. In these experiments, Agilent solar simulator E4367A is used as the power source of the developed PV charger. Two series-connected 12V/7Ah acid-lead batteries are used as the load. The overcharging voltage $V_{oc}$, the float-charging voltage $V_b,f$, and the preset pulse-charging voltage $V_b,set$ are 27.6V, 27.2V and 26.4V, respectively. Figure 9(a) shows the measured waveforms for MPP tracking by using the studied $R_{\text{ds(on)}}$ current-sensing technique under 7V input voltage (at an MPP of 4W). Figure 9(b) demonstrates the measured MPPT waveforms under 17V input voltage (at an MPP of 24W). It can be observed that the actual tracked powers are 3.9W and 23.7W, respectively. Figure 10 shows the performance comparisons between the studied $R_{\text{ds(on)}}$ current-sensing and the conventional current-sensing techniques. As shown in Figures 10(a) and 10(b), highest conversion efficiency and MPPT accuracy can be achieved by using the hall-effect sensor. Nevertheless, the hall-effect sensors are too expensive and huge for studied MIC applications. The current-sensing resistor technique has the advantages of low cost and good frequency-response features. However, its conversion efficiency is the worst due to extra resistive loss. A sensed error for PV array voltage $V_{pv}$ occurs due to the addition of a current-sensing resistor to deteriorate MPPT accuracy. The studied $R_{\text{ds(on)}}$ current-sensing technique presents the best performance considering the circuit miniaturization, circuit cost and overall efficiency. Figure 11(a) and 11(b) respectively show the measured PWM synchronous waveforms under in-phase and out-of-phase operations realized by the studied I$^2$C interface scheme. Figure 12(a) shows the measured pulse-charging waveforms around 78 percent charge-period on battery side. During the rest period, battery electrolyte reaction can be relaxed to prolong battery lifetime. Figure 12(b) shows the measured interleaved waveforms on battery side. Ripple cancellation on the battery current can be achieved by using the studied I$^2$C communication to realize the interleaved operation. A battery capacity tester TES-33 is used to measure the long-term waveforms for battery voltage and current during the battery charging process. As shown in Figure 13, the MPPT charging proceeds first. At a constant power input condition, the battery current decreases slightly while the battery voltage increases. When the battery voltage rises to 26.4V ($V_{b,set}$), a pulse-charging current is sent to battery. The average battery current decreases rapidly in accordance with the reduction of its pulse width. Figure 14(a) shows the measured pulse-charging waveforms on PV panel side. During the charge-period, a MPP tracking above 98 percent accuracy is maintained to extract the maximum power of PV panel. The interleaved waveforms on PV panel side are shown in Figure 14(b). Ripple cancellation between the input currents of the parallel-connected PV chargers can be observed. Only one small polypropylene thin-film capacitor is used at battery side, no electrolytic capacitor is needed.
Table 1 Circuit Parameters for the Laboratory Prototype.

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Label</th>
<th>Value/Part No.</th>
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<tbody>
<tr>
<td>Power Switches Q1, Q2</td>
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</tr>
<tr>
<td>Output Diodes D1, D2</td>
<td>UF3D</td>
<td></td>
</tr>
<tr>
<td>Boost Chokes L1, L2</td>
<td>100μH</td>
<td></td>
</tr>
<tr>
<td>Output Capacitors C1, C2</td>
<td>10μF polypropylene thin film</td>
<td></td>
</tr>
</tbody>
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Figure 9 MPPT Waveforms under (a) 7V and (b) 17V Input.

Figure 10 Performance Comparisons among Three Current-Sensing Techniques (a) Conversion Efficiency, (b) MPPT Accuracy and (c) Overall Efficiency.

Figure 11 Measured Synchronous Waveforms (a) In-Phase and (b) Out-of-Phase Operations.

Figure 12 Measured Waveforms for (a) Pulse-Charging Operation and (b) Interleaved Operations on Battery Side.

Figure 13 Measured Battery Voltage and Current Waveforms during the Charging Process.
This paper presents a modular PV charger with MPP tracking and pulse-charging schemes. An I²C interface is adopted to realize the interleaved operation for the parallel-connected PV chargers. Current ripple cancellation among the PV chargers can be achieved to reduce the filtering elements. In the experimental verifications, the MPPT accuracy of the developed PV charger can be achieved above 96 percent by using the studied $R_{ds(on)}$ current-sensing technique. A pulse-charging scheme without extra battery-current sensor is also designed to prolong the battery lifetime.

V. CONCLUSION

This paper presents a modular PV charger with MPP tracking and pulse-charging schemes. An I²C interface is adopted to realize the interleaved operation for the parallel-connected PV chargers. Current ripple cancellation among the PV chargers can be achieved to reduce the filtering elements. In the experimental verifications, the MPPT accuracy of the developed PV charger can be achieved above 96 percent by using the studied $R_{ds(on)}$ current-sensing technique. A pulse-charging scheme without extra battery-current sensor is also designed to prolong the battery lifetime.

REFERENCE


VI. BIOGRAPHIES

Huang-Jen Chiu (M’00-SM’09) received the B.E. and Ph.D. degrees in electronic engineering from National Taiwan University of Science and Technology (NTUST), Taipei, Taiwan, in 1996 and 2000, respectively. From August 2000 to July 2002, he was an Assistant Professor in the Department of Electronic Engineering, I-Shou University, Kaohsiung, Taiwan. From August 2002 to July 2006, he was with the Department of Electrical Engineering, Chung-Yuan Christian University, Chung-Li, Taiwan. Since August 2006, he has been with the Department of Electronic Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, where he is a Professor now. In 2009, he joined the Future Energy Electronic Center, Virginia Polytechnic Institute and State University, as a Visiting Professor. His research interests include renewable energy conversion, high efficiency LED driver, and PFC topologies. Dr. Chiu is a senior member of the IEEE Power Electronics Society. He is the recipient of the Young Researcher Award in 2004 from the National Science Council, Taiwan, the Outstanding Teaching Award and the Excellent Research Award in 2009 from the NTUST.

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