A New Distributed MPPT Technique using Buck-only MICs Linked with Controlled String Current

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A novel idea to realize the distributed maximum power point tracking (DMPPT) control of a photovoltaic system interfaced with an AC grid is proposed. The proposed system is based on the idea of string-connected dc-dc module integrated converters (MICs) that was researched by Walker, Erickson, and others. However, those studies focused on working together with a voltage source inverter (VSI) in a constant DC voltage mode. In addition, all commercial products from companies such as Solar Edge, Solar Magic, and Tigo Energy are working together with a VSI in a constant DC voltage mode. In contrast to past works, the proposed system uses controlled string current with a current source inverter (CSI) to link MICs. As a result, the circuit topology and control scheme of the MICs have been greatly simplified. The authors hope that the proposed system is especially suited for SiC-based CSI applications in the near future. This paper first reviews the conventional control schemes. Then a new MIC-based DMPPT technique is proposed. A simulation study using PSIM is conducted to prove the validity and usefulness of the proposed system. Finally, the successful experimental operation of peak power tracking was confirmed by using two cascaded MICs.

Keywords: PV system, DMPPT, dc-dc MIC, CSI, SiC

1. Introduction

Given the future exhaustion of natural fossil energy resources and global warming control, the practical use of renewable energy is becoming important throughout the world, especially in Japan, where the accident at the Fukushima nuclear power station was followed by the 3.11 Great East Japan Earthquake on March 11, 2011. These events resulted in a serious change in the long-term energy strategy of the Japanese government. Even before the earthquake, the Japanese government was planning to introduce 53 GW of photovoltaic generation before 2030, which corresponds to about one-fourth of the total electric power capacity of the Japanese islands. The strategy is now under review, and includes the possibility of resuming the operation of nuclear power stations. For these reasons, expectations for renewable energy utilization cannot help but attract a lot of attention. There are several plans to construct mega solar systems in vacant lots where the citizens who escaped from the tsunami or radioactive disasters used to live. On the other hand, residential photovoltaic (PV) systems are also rapidly growing with the help of the feed-in tariff government policy that began in November 2011. The appearance of attractive home energy management systems that combine PVs, fuel cells, and the batteries of electric vehicles are another primary factor in promoting the introduction of PV systems.

Using this background, this paper presents a new MIC-based DMPPT technique to maximize the output power of the PV system. So far, the conventional DMPPT PV system focused on working together with VSI at a constant DC voltage. The VSI is a unit that has been most widely used for linking the AC grid to MICs in a PV system. However, this requires a stable high input voltage and a large electrolytic capacitor, which determines the product lifetime of the system. On the other hand, the CSI was rarely used by industry, which requires devices that have low on-resistance and high reverse voltage. However, thanks to the development of SiC FETs, SiC-based CSI applications are expected to be used in the near future. By using a CSI instead of a VSI, the large electrolytic capacitor can be removed from the power conditioning system (PCS). As a result, the reliability of the PV system will be greatly improved. The goal of this paper is to introduce a new concept of a PV system that is based on a controlled string current with CSI. First, a nonuniform insolation problem and conventional countermeasures are described. Second, a new MIC-based DMPPT technique is proposed. A simulation study using PSIM is carried out to prove the validity and usefulness of the proposed system. Finally, some successful experimental results with two prototype cascaded MICs are shown to prove their validity and usefulness.

2. Conventional Control Schemes

2.1 Nonuniform Insolation Problems

As shown in Fig. 1, the opportunity to install PV arrays on nonideal rugged or uneven surfaces is increasing. However, uniform
insolation is not guaranteed, and there is a possible imbalance of insolation or partial shading. In a typical PV system, PV modules are connected in series, forming a string to satisfy the required voltage rating of the PV array. In addition, several numbers of strings are connected in parallel by using combiner diodes to satisfy the required current rating. This is shown in Fig. 2. This series string connection circuit topology has an inherent drawback against partial shading. Even if only one panel within a string is shaded, the nonshaded panels are affected because the string current is limited by the shaded panel. A well-known and simple countermeasure is to attach a bypass diode to each module. However, the current bypassed module is completely cut off from the system and has no contribution even if its insolation is not zero.

### 2.2 Conventional MIC-based Scheme

A better solution to solve the partial shading problem lies in applying MIC-based techniques. There are two types of MIC-based approaches: dc-ac MIC type and dc-dc MIC type. These approaches are shown in Fig. 3. Some commercial products of dc-ac MIC are supplied by Enphase Energy. A typical dc-ac MIC type is composed of a chopper and a micro-inverter. Since every dc-ac MIC type is connected in parallel with the AC grid, independent MPPT operation is possible in this system. By contrast, the dc-dc MIC type was first proposed by G.R. Walker et al. and improved by R.W. Erickson et al. (2) (4). Figure 3(b) shows Erickson’s dc-dc MIC type. Each MIC is comprised of tandem connected buck and boost converters and several switches for a “pass-through mode.” The output terminals are connected in series and are connected to the DC link capacitor of the PWM VSI for AC grid interfacing. The DC link voltage, i.e., the string voltage, is kept constant by the voltage feedback loop of the PWM VSI. Each MIC has three operating modes according to its string current $I_{\text{string}}$ and PV array current $I_{\text{PV}}$. The modes are as follows: (i) buck mode ($I_{\text{PV}} < I_{\text{string}}$), where the buck converter decreases the voltage to keep up with the string current; (ii) boost mode: ($I_{\text{PV}} > I_{\text{string}}$), where the boost converter increases voltage to match to lower string current; and (iii) pass-through mode ($I_{\text{PV}} \approx I_{\text{string}}$), where the input is directly connected to the output. A MPPT algorithm is carried out independently at each MIC based on the measured voltage $V_{\text{PV}}$ and current $I_{\text{PV}}$ of the PV array in real time.

Some commercial products based on similar principles are available from STMicroelectronics, in which only the boost converter with a built-in MPPT algorithm is applied (5). A typical product is the SPV1020 power chip, which has a power capability of 320 W at 40 V output.

Compared with the dc-dc MICs, the dc-ac MICs degenerate the efficiency of the PV system because each dc-ac MIC must carry both the dc/dc converter and dc/ac converter in the module. On the other hand, the typical dc-dc MIC (such as Ericson’s MIC, which was adopted by Solar Magic) must carry three mode circuits. Thus, the typical dc-dc MIC is complex. In particular, the common drawback of a PV system that uses conventional MICs is the necessity for a electrolytic capacitor in the inverter.

### 2.3 Proposed New MIC-based Scheme

This paper proposes a promising new trend of a string connected dc-dc MIC-based PV system. Figure 4 shows the operating principle. In this system, each MIC has a buck chopper topology. The MICs’ output terminals are connected in series with the controlled current source link of the PCS for AC grid interfacing. The control rules of this system are quite simple: (i) each MIC is controlled to maximize its output voltage irrespective of the string current amplitude, and (ii) the PCS optimizes the amplitude of the string current. By following these two rules at the same time, the entire system is led to a maximum power operating condition.
The condition illustrated in Fig. 4 shows that the top of the MIC is given strong insolation, and the bottom of the MIC is given weak insolation. In the dc-dc MIC type PV system, each output current of the MIC must be the same current because the output nodes are connected in series. Therefore, in this case, the bottom of the MIC’s output current increases to correspond to the string current. As a result, its output voltage is reduced, keeping its PV maximum power. This operation is done automatically using MPPT by the microcomputer, which contained in each MIC.

To understand this operation, the following basic experiments have been carried out. One stage of the buck converter is picked up and tested, as shown in Fig. 5. Figure 5(a) shows the measurement setup for a single buck converter. Here, a solar-array simulated power supply (SAS) was used instead of a PV panel. The open voltage $V_{oc}$ is set to 30 V, and the short current $I_{sc}$ is set to 0.6 A. The output node $V_{out}$ is connected to the load resistance $R_L$, and the duty ratio $d$ is controlled manually by the pulse generator. Figure 5(b) shows the $V_{out}$ vs. $I_{string}$ characteristics, which are obtained by varying the value of $R_L$. When the duty ratio $d = 0.9$, the buck converter’s output voltage $V_{out}$ is relatively high, and the string current $I_{string}$ is relatively low. On the other hand, when the duty ratio $d = 0.4$, the buck converter’s output voltage $V_{out}$ decreases, and the string current $I_{string}$ increases. The blue circles in Fig. 5(b) are the maximum power point of each duty ratio. Although the duty ratio $d$ was changed manually in Fig. 5, it was changed automatically by the MPPT in the actual system. Since the buck converter ideally has no loss, each maximum power setting has the same value even when the duty ratio $d$ changes. This means that the buck converter in Fig. 4 plays the role of an impedance transformer.

### 3. Simulation Studies

The simulation studies were carried out using PSIM. Figure 6 shows the entire simulated system. The Buck1 block and MPPT1 block consist of a MIC, and the MIC is connected in series as shown in Fig. 6(a). Here, two cascaded MICs were tested. The current source $I_{string}$ was used instead of the CSI. The PV was formed by the behavior model, as shown in Fig. 6(b). The open voltage was set to 30 V, and the short current was set to 1.88 A. The value of 1.88 A comes from the short current value of Shell Solar SJJ30. The buck converter was modeled by a transistor level, and its switching frequency was set to 25 kHz, as shown in Fig. 6(c). The internal part of the MPPT block was coded in the C language. The MPPT algorithm adopted the perturb and observation (P&O) method, which controls the duty ratio of the buck converter to maintain the peak power of the PV.

Figure 7 shows the simulation results. The time-varying insolation intensity is modeled by the time-varying short circuit current of the PV2 panel. The insolation intensity of PV1 is fixed at 1.88 A. According to the alternative intensity changes from 1.88 A to 0.94 A, the output power $P_{panel2}$ of the module successfully tracks the maximum power point, whereas the string current is kept at a constant value of 2 A, which is chosen to be a slightly larger value than the short-circuit current.
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Fig. 7. Simulation results showing successful tracking of maximum power point according to insolation change

Fig. 8. Simulation results of optimum string current scanning, which enables the maximum total system output power

at the full (strongest) insolation of the PV module (1.88 A). Likewise, the buck converter’s output $V_{out2}$ follows the insolation changes.

Figure 8 shows a characteristic curve that details the results of optimum string current searching, which enables the maximum total system output power. The optimum current search is controlled by changing the string current $I_{string}$. We can see that the optimum string current is approximately 2 A. The reason for the slope over approximately 4 A of $P_{out}$ is the loss of the buck converter. For this simulation, the reference value of the string current was changed manually from 0 A to 10 A. However, in a real system, the string current command is slowly changed to scan the maximum power point in real time.

From the simulation results in Fig. 7 and Fig. 8, the proposed system will operate without problems even if multiple MICs are applied more than two cascaded MICs and share a common controlled string current.

4. Experimental Results

To assess the usefulness of the proposed module integrated converter system, a prototype measurement system was implemented. Figure 9 shows the block diagram of the measurement system. The solar array simulator “Soldio” SS-301 (Fukushima Electronic) was used instead of a solar panel. The buck converters are located between the solar array simulators SS-301 and a programmable DC Electric Load 3700 (Array Electronic). The Electric Load is an assumed the current-type inverter, and its operation mode is chosen as a constant current mode. The control circuits are realized by a microcomputer board SH7144F (Akizuki Denshi), which includes 10-bit AD converters with a 12.5-MHz CPU clock. The MPPT algorithm is realized by this microcomputer program. The voltage ($V_{panel}$) and current ($I_{panel}$) of each solar panel are measured, and the nodes are tied to the microcomputer. The output powers of PV1, PV2, and the total output node $V_{string}$ are measured by a power analyzer WT500 (Yokogawa Electric).

Figure 10 shows schematics of the buck converter. Inductor $L_1$ and output capacitor $C_{out}$ were selected to be 220 $\mu$H and 47 $\mu$F, respectively. The value of inductor $L_1$ was chosen to operate in continuous conduction mode for the buck converter. The operational frequency of the buck converter was designed to be approximately 25 kHz. To reduce the switching noise, a bypass capacitor $C_{in}$ (47 $\mu$F) was connected close to the drain node of $M_1$. Here, although we used the electrolytic capacitor for $C_{out}$ and $C_{in}$ on this first evaluation board, it can be substituted with a film capacitor. A voltage sensor LEM LV25-P and current sensor LEM LA55-P were connected to measure the output voltage and current.
of the simulated power supply PV1 for P&O operation. An isolator TLP250 isolates the microcomputer from the buck converter. The supply voltages of the voltage sensors LV-25P and TLP250 were supplied by the DC-DC converter cc1R5-1212. To prevent reverse current during an illegal start-up, a Schottky barrier diode D1 was connected between PV1 and the buck converter.

Figure 11 shows a photograph of the implemented buck converter and the SH7144F microcomputer board. The board size of the buck converter is approximately 85 mm × 65 mm.

Figure 12 shows the transient waveform of V\text{string} when the system is powered on. Voc1 and Voc2 are set to 30 V, and Ish1 and Ish2 are set to 2 A, under the string current I\text{string} = 2 A. We can see that its rise time (10–90%) was approximately 3.8 s with no overshoot and a slight oscillation owing to P&O.

In order to check the total maximum power, three cases of V-P characteristic curves are prepared using a solar array simulated power supply SS-301. Figure 13 shows the measured V-P characteristic curves. Figure 13(a) shows two curves, i.e., Ish1 = 1.5 A and Ish2 = 0.6 A, under the same open voltage (Voc = 50 V). The maximum power of PV1 was 31.1 W, and the maximum power of PV2 was 14.1 W. Figure 13(b) shows the two curves, i.e., Voc1 = 15 V and Voc2 = 30 V, under the same short current (Ish1 = Ish2 = 1.5 A). The maximum power of PV1 was 31.1 W, and the maximum power of PV2 was 9.7 W. Figure 13(c) shows the condition of Ish1 = Ish2 = 0.6 A and Voc1 = Voc2 = 30 V. The maximum power of PV1 was 17.1 W, and the maximum power of PV2 was 14.1 W. The slight difference in maximum power in Fig. 13(c) is caused by the variation between two different solar array simulated power supplies (SS-301).

Figure 14 shows the confirmation results of our proposed system. The results definitely capture the maximum power points for total power. Here, the dotted lines represent the output power depending on the string current I\text{string}. The solid lines show the total efficiency, including the two buck converters. In Fig. 14(a), we can see that maximum power Pout is 41.8 W (max) at 1.5 A, which corresponds to the sum of 31.1 W (max) and 14.1 W (max) considering the efficiency of the buck converters. Likewise, in Fig. 14(b) we can see that maximum power Pout is 38.1 W (max) at 1.5 A, which corresponds to the sum of 31.1 W (max) and 9.7 W (max) considering the efficiency of the buck converters. Again, in Fig. 14(c), we can see that maximum power Pout is 29.7 W (max) at 0.7 A, which corresponds to the sum of 29.7 W (max) and 9.7 W (max) considering the efficiency of the buck converters.

5. Conclusions

This paper has presented a novel string MIC-based PV system enabling distributed MPPT. It is characterized with the controlled string current linked topology, whereas the conventional string MIC-based schemes are based on controlled voltage linked topologies. The new proposed scheme is considered to be the dual system of the conventional one in operational principle. The experimental prototype demonstrates...
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In this paper, the current source inverter is modeled with a current source and the case with a two cascaded string as shown in Fig. 9 has been considered both in simulation and experiment to confirm the basic operation principle. In the case with over two cascaded strings connected in parallel, it is considered that the each string current automatically reaches its steady state condition based on the whole system’s power equilibrium conditions.

The authors hope that the proposed system is especially suited for next-generation SiC-based current source inverter applications.

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