Control of Cascaded H-Bridge Multilevel Inverter with Individual MPPT for Grid-Connected Photovoltaic Generators

Bailu Xiao[1], Ke Shen[2], Jun Mei[3], Faete Filho[1], Leon M. Tolbert[1]

[1]Department of Electrical Engineering and Computer Science
The University of Tennessee
Knoxville, TN 37996, USA

[2]Department of Electrical Engineering
Harbin Institute of Technology
Harbin 150001, China

[3]Department of Electrical Engineering
Southeast University
Nanjing 210096, China

***Abstract*—A single-phase cascaded H-bridge multilevel inverter for a grid-connected photovoltaic (PV) system with nonactive power compensation is presented in this paper. To maximize the solar energy extraction of each PV string, an individual maximum power point tracking (MPPT) control scheme is applied, which allows the independent control of each dc-link voltage. A generalized nonactive power theory is applied to generate the nonactive current reference. Within the inverter's capability, the local consumption of nonactive power is provided to realize power factor correction. A single-phase modular cascaded multilevel inverter prototype has been built. Each H-bridge is connected to a 195 W solar panel. Simulation and experimental results are presented to validate the proposed ideas.**

I. INTRODUCTION

Nowadays, there has been an increasing interest in electrical power generation from renewable energy, and solar energy has been one of the most attractive research areas. Photovoltaic (PV) systems are ideally distributed generation (DG) units, and they offer the advantages of being pollution free and little maintenance. Solar-electric-energy demand has grown consistently by 20%-25% per annum over the past 20 years [1], and the growth is mostly in grid-connected applications. Utilities are adapting to solar as their fastest growing electricity source. In 2011, utilities in the US interconnected over 62,500 PV systems, and conservative forecasts indicate that this number will grow to more than 150,000 interconnections in 2015 [2].

A PV inverter, which is used to convert DC power from the solar panels into AC power to be fed into the grid, is an important element in the grid-connected PV system. Many different types of PV inverters have been proposed and studied [3-5]. The cascaded H-bridge multilevel inverter requires an isolated DC source for each H-bridge; thus, the high power and/or high voltage from the combination of the multiple modules would favor this topology in medium and large grid-connected PV systems [6-8]. In addition, the separate DC links in the multilevel inverter make the independent voltage control possible. As a result, individual maximum power point tracking (MPPT) control in each string can be achieved, and the energy harvested from PV panels can be maximized. Meanwhile, the modularity and low cost of multilevel converters would position them as a prime candidate for the next generation of efficient, robust, and reliable grid-connected solar power electronics.

A single-phase cascaded H-bridge multilevel inverter topology for a grid-connected PV system is presented in this paper. The panel mismatch issues are addressed to show the necessity of individual MPPT control, and a control scheme with independent MPPT control in each string is then proposed.

At higher penetrations, the impact of PV systems may accumulate and affect power quality. The nonactive power control of PV inverters provides an opportunity to maintain good power quality in the grid and optimize the performance of distribution circuits. In this paper, the options of nonactive power control are discussed. A generalized nonactive power theory is applied to generate the nonactive current reference. Besides providing the active power, the photovoltaic grid-connected cascaded H-bridge multilevel inverter could also provide the nonactive power required by the local load to realize power factor correction and minimize distribution losses.

Finally, a single-phase modular cascaded multilevel inverter prototype has been built. Each H-bridge is connected to a 195 W solar panel. The modular design will increase the flexibility of the system, and reduce the cost as well. Simulation and experimental results are provided to demonstrate the developed control scheme.

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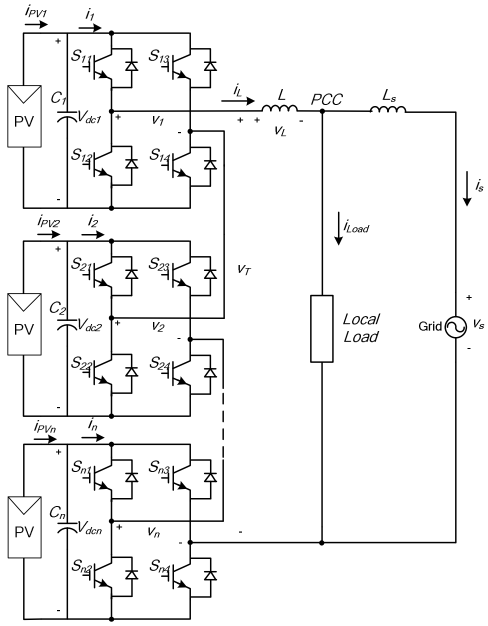


Fig. 1. Topology for the grid-connected system.

II. System Description

The cascaded multilevel inverter topology consists of n H-bridge converters connected in series and is shown in Fig. 1. Each DC link is fed by a short string of PV panels. By different combinations of the four switches in each H-bridge, three output voltage levels can be generated, $-v_{dc}$, 0, or $+v_{dc}$. A cascaded multilevel inverter with n input sources will provide $2n+1$ levels to synthesize the AC output waveform. This $(2n+1)$-level voltage waveform enables the reduction of harmonics in the synthesized current, reducing the output filters. Multilevel inverters also have other advantages such as reduced voltage stresses on the semiconductor switches, as well as having higher efficiency when compared to other converter topologies [9].

As shown in Fig. 1, the cascaded multilevel inverter is connected to the grid through an L filter, which is used to reduce the switching harmonics in the current. There is also a local load connected in parallel. PV power is delivered to the load/grid according to the system operation conditions.

III. Control System

A. Panel Mismatches

A control scheme of the single-phase cascaded H-bridge multilevel inverter for a grid-connected PV system is proposed in [10]. The control scheme is based on the classical scheme for the control of a single H-bridge converter connected to the grid [11, 12]. To harvest more energy from the PV panels, an MPPT controller is added to generate the dc-link voltage reference. The solar energy extraction is maximized if all the PV panels are operating under the same condition.

However, due to the unequal received irradiance, different temperature and aging of the PV panels, the maximum power points (MPPs) of each PV string may be different. The efficiency of the overall PV system will be decreased if there is mismatch between the strings.

To show the necessity of individual MPPT control, a 5-level two H-bridges inverter is simulated with the control scheme proposed in [10]. Each H-bridge has its own 195 W PV panel connected as an isolated DC source. The PV panel is modeled according to the specification of the commercial PV panel from Sanyo, HIP-195BA19.

Consider an operating condition that each panel has a different irradiation from the sun; panel 1 has irradiance S = 1000 W/m^2, and panel 2 has S = 600 W/m^2. As shown in Fig. 2, the power extracted from panel 1 is around 147 W, and the power from panel 2 is 60 W. The total power harvested from the PV system is 207 W.

However, Fig. 3 shows the MPPs of the PV panels under the different irradiance. The maximum output power is 195 W and 114.6 W respectively when S = 1000 W/m^2 and 600 W/m^2, which means the total power harvested from the PV system would be 309.6 W if individual MPPT can be achieved. This higher value is about 1.5 times of the one before.

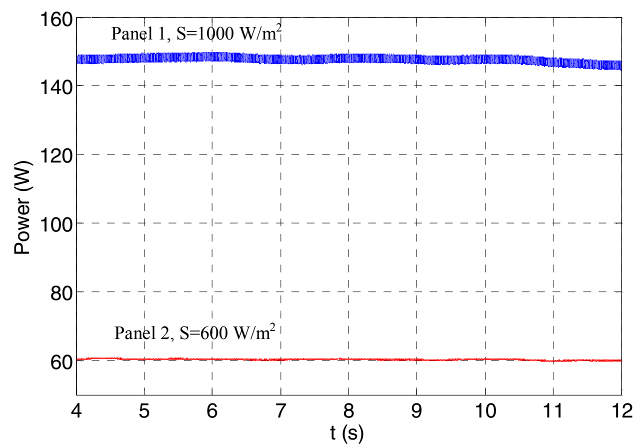


Fig. 2. Power extracted from two PV panels.

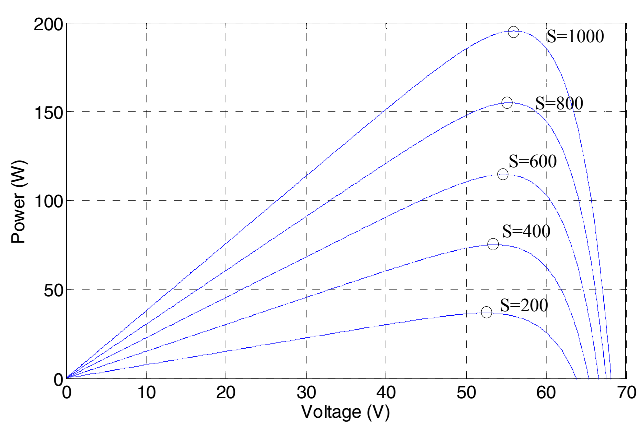


Fig. 3. *P-V* characteristic under the different irradiance.

B. Control Scheme

In order to eliminate the adverse effect of the mismatches and increase the efficiency of the PV system, the PV strings need to operate at different voltages to maximize the energy harvested from each string.

The separate DC links in the cascaded H-bridge multilevel inverter make independent voltage control possible. To realize individual MPPT control in each string, the control scheme proposed in [13] is updated for this application, as shown in Fig. 4.

In each string, an MPPT controller is added to generate the dc-link voltage reference. Each dc-link voltage v_{dci} is compared to the corresponding voltage reference v_{dciref}, and the sum of the errors is controlled through a PI controller that determines the active current provided by the multilevel inverter. Nonactive current reference i_{nref} is obtained by using a generalized nonactive power theory, which will be discussed in the next section. The current controller gives the sum of the modulation index of each H-bridge inverter.

The voltages v_{dc2} to v_{dcn} are controlled individually through *n-1* loops. Each voltage controller gives the modulation index of one H-bridge module. After obtaining *n* modulation indices, phase-shifted SPWM (PS-SPWM) switching scheme is applied to control the switching devices of each H-bridge.

Many MPPT methods have been developed and implemented [14, 15]. The incremental conductance method has been used in this paper. It lends itself well to digital control, which can easily keep track of previous values of voltage and current, and make all the decisions.

IV. Nonactive Power Control

A. Power Quality vs. Distribution Loss Reduction

High-penetration levels of PV generation present challenges to distribution utilities. Despite the challenges, there is also an opportunity for the utility to enhance its performance with the grid-connected PV inverters [16-18]. For example, the nonactive power control of PV inverters provides an opportunity to improve power quality and reduce distribution losses in the grid. However, equations (1) and (2) provide an excellent expression for gaining intuition about the competing nature of minimizing the voltage variation and reducing distribution circuit losses [18].

The rate of energy dissipation E_j and the change in voltage ΔV_j between nodes j and $j+1$ of the distribution circuit are given by

$$E_j = r_j \frac{P_j^2 + Q_j^2}{V_0^2} \tag{1}$$

$$\Delta V_j = -\frac{r_j P_j + x_j Q_j}{V_0} \tag{2}$$

where P_j and Q_j represent active and nonactive power flowing down the circuit from node j, V_j is the voltage at node j, r_j+ix_j is the complex impedance of the link between node j and $j+1$, as shown in Fig. 5.

Equation (1) shows that losses in any circuit segment j are minimized when $Q_j = 0$, which means the consumption and generation of nonactive power at the node should be equal. However, (2) shows that $Q_j = -r_jP_j/x_j$ is needed to minimize the voltage variation, which is in clear competition with loss reduction. Therefore, nonactive power compensation that provides optimal voltage regulation and minimizes losses simultaneously should not be expected.

Due to the competition between optimal voltage regulation and minimization of losses, there are three nonactive power control options: (1) control on local voltage only, (2) control on local flow only, and (3) hybrid control, which considers both local voltage and power flow. The control algorithm based on local voltage only is proposed in other papers. In this paper, the control scheme

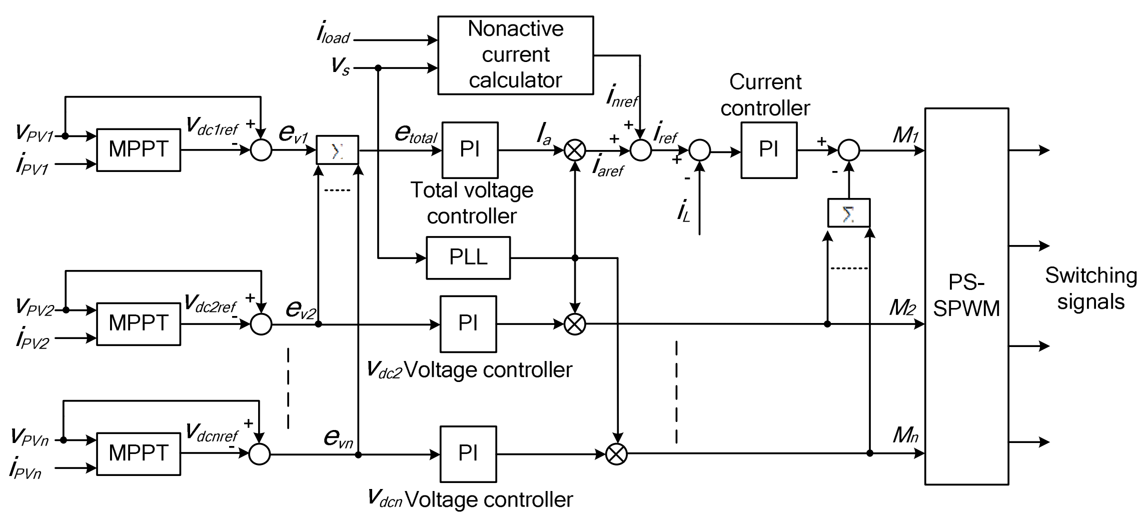


Fig. 4. Control scheme.

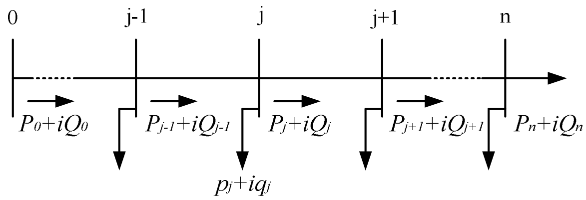


Fig. 5. Diagram for the radial network.

is based on local flow that losses are minimized when nonactive power flows Q_j are zero. The local consumption of nonactive power is supplied by the PV inverter up to the limits imposed by its capacity and generation, and power factor correction is achieved.

B. Generalized Nonactive Power Theory

To provide the local consumption of nonactive power, generalized nonactive power theory [19] is applied to calculate the nonactive current reference. Consistent with the standard steady-state power definitions, this theory is an extension of the standard definitions and other instantaneous power theories. The defined instantaneous active and nonactive power and/or current are valid in various power systems, whether single-phase or multi-phase, sinusoidal or non-sinusoidal, periodic or non-periodic, balanced or unbalanced.

Considering the power system in this paper, the average power of the local load is denoted as $P(t)$:

$$P(t)=\frac{2}{T}\int_{t-\frac{T}{2}}^{t} v_{Load}(\tau)i_{Load}(\tau)d\tau \tag{3}$$

The instantaneous active current of the local load $i_a(t)$ is defined by

$$i_a(t)=\frac{P(t)}{V_p^2(t)}v_p(t) \tag{4}$$

where $v_p(t)$ is the reference voltage, and $V_p(t)$ is the rms value of $v_p(t)$. In this paper, the grid voltage is chosen as the reference voltage.

Then, the instantaneous nonactive current of the local load $i_n(t)$ is defined by

$$i_n(t)=i_{Load}(t)-i_a(t) \tag{5}$$

Assuming the instantaneous local load current could be measured by a local smart meter, the instantaneous nonactive current is calculated as the nonactive current reference of the multilevel inverter. Thus, the nonactive current in the local load will be supplied by the cascaded H-bridge multilevel inverter, and the point of common coupling will be operated at unity power factor.

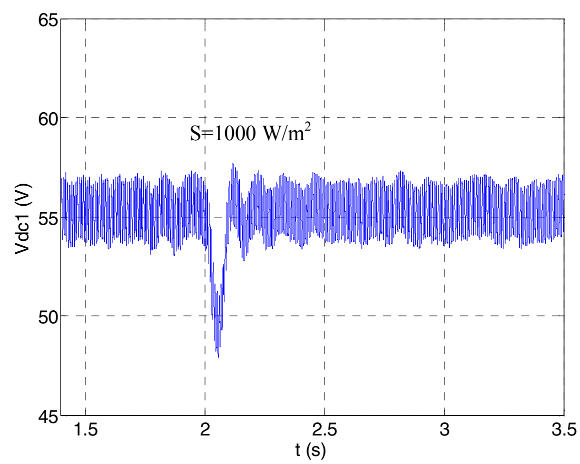
The nonactive generation is limited by the inverter capacity, and the nonactive current reference is also limited. However, the nonactive power of the local load will be compensated to the greatest degree possible by the multilevel inverter, which helps to reduce the distribution circuit losses.

V. Results

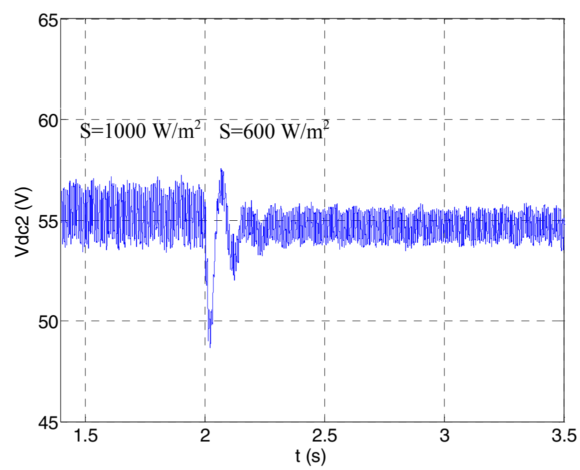
Simulation and experimental tests are carried out to validate the proposed ideas. A single-phase modular cascaded multilevel inverter prototype has been built. Each H-bridge has its own 195 W PV panel (Sanyo HIP-195BA19) connected as an independent source. For simplicity and to easily appreciate the control principle, only two H-bridge modules will be considered in the simulation and experimental tests. The system parameters are shown in Table I.

TABLE I. System Parameters

Parameters	Value
DC-link capacitor	3600 µF
Connection inductor L	3 mH
Load inductor	20 mH
Load resistor	20 ohm
Grid rated RMS voltage	48 V
Switching frequency	1.8 kHz



(a) DC-link voltage of module 1



(b) DC-link voltage of module 2

Fig. 6. DC-link voltage of two modules (T=25 °C).

To verify the individual MPPT control scheme, the 5-level inverter is operated in two different conditions. First, two PV panels are operated under the same irradiance S = 1000 W/m^2 and temperature T = 25 ˚C. At t = 2s, the solar irradiance on the first panel stays the same, and that for the second panel decreases to 600 W/m^2. The dc-link voltage waveforms of two modules are shown in Fig. 6. As the irradiance changes, the second dc-link voltage decreases and tracks the new MPP voltage of the second PV panel.

The PV current waveforms are shown in Fig. 7. It can be seen that the lower irradiation affects the current in the second PV panel, so the lower ripple of the dc-link voltage can be found in Fig. 6(b).

Fig. 8 shows the power extracted from the two panels. At the beginning, both panels are operated under irradiance S = 1000 W/m^2 and generating maximum power 195 W. After t = 2s, when the solar irradiance over the second panel decreases to 600 W/m^2, the power extracted from panel 1 is still 195 W, and the power from panel 2 is 114.5 W. According to the *P-V* characteristic shown in Fig. 3, each PV panel is operating at its own maximum power point, and individual MPPT is achieved.

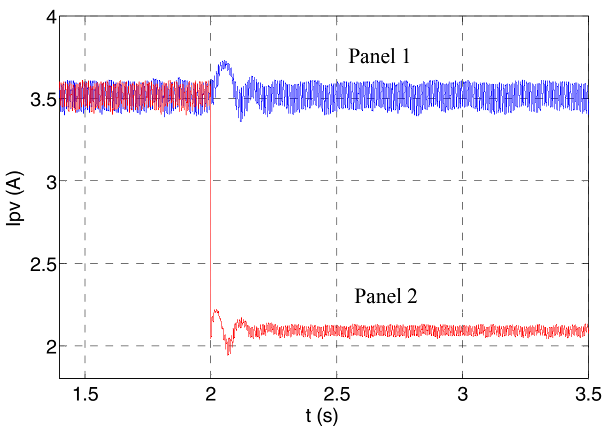


Fig. 7. PV current of two modules (T=25 ˚C).

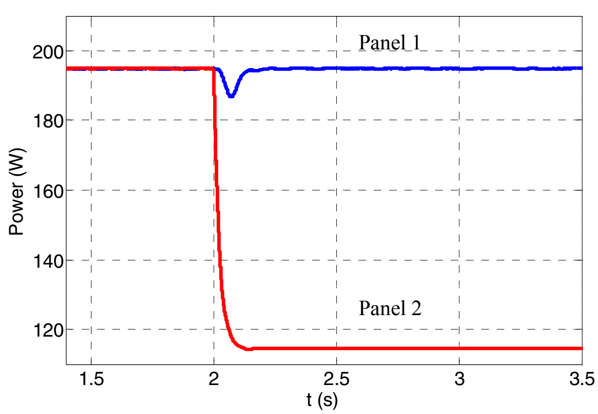


Fig. 8. Power extracted from two PV panels with individual MPPT.

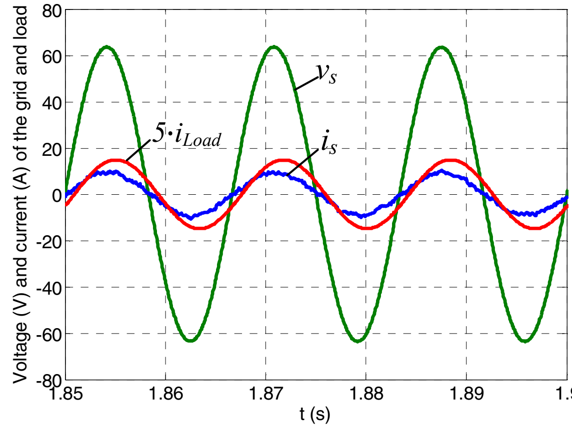


Fig. 9. Voltage and current waveforms of grid and load.

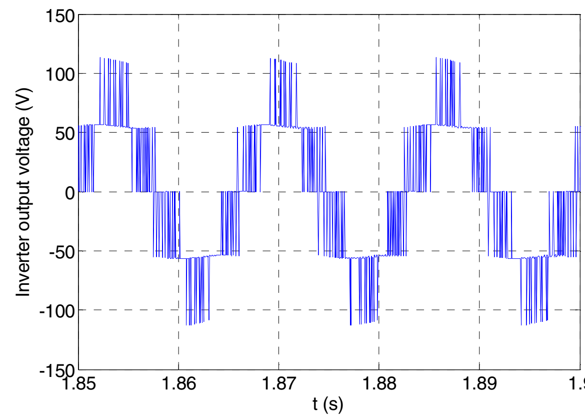


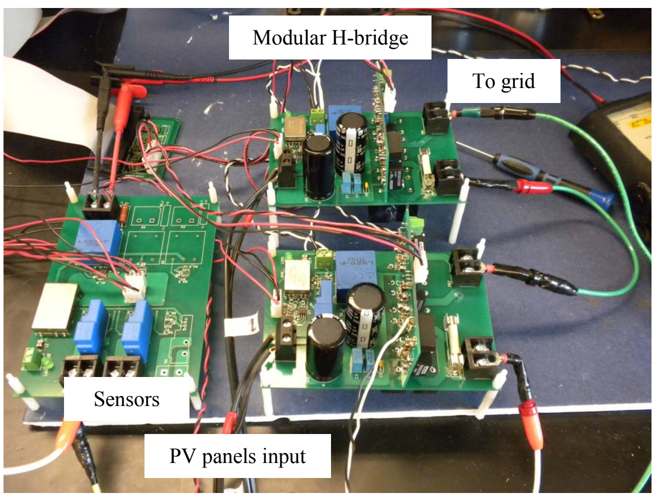
Fig. 10. Inverter output voltage.

The voltage and current waveforms of the grid and load are shown in Fig. 9. It can be seen that the load current is lagging the grid voltage, however, the grid current has the same phase as the voltage, which means the grid has unity power factor. The output voltage of the multilevel inverter is shown in Fig. 10. The 5-level voltage helps to reduce the output filters.

A modular cascaded multilevel inverter prototype has been built in the laboratory. The modular design will increase the flexibility of the system, and reduce the cost as well. The MOSFET IRFSL4127 is selected as inverter switches operating at 1.8 kHz. The control signals to the H-bridge inverters are sent by the dSPACE ds1103 controller. Fig. 11 shows the experimental solar panels and the 5-level cascaded multilevel inverter.

The experimental results are presented in Fig. 12 and Fig. 13. Fig. 12 shows the grid voltage, current and the dc-link voltage of two H-bridge modules. It can be seen that the two dc-link voltages are controlled independently, which means individual MPPT can be achieved. Fig. 13 shows the grid voltage and current, the load current and the inverter output voltage. The experimental results also show that the grid current has the same phase as the grid voltage and has unity power factor. The THD of the grid current is 4.7%, as shown in Fig. 14, which is less than 5% and meets the power quality standards, like IEEE1547 in the US and IEC61727 in Europe.

(a) Solar panels Sanyo HIP-195BA19



(b) Modular 5-level cascaded multilevel inverter

Fig. 11. Experimental prototype.

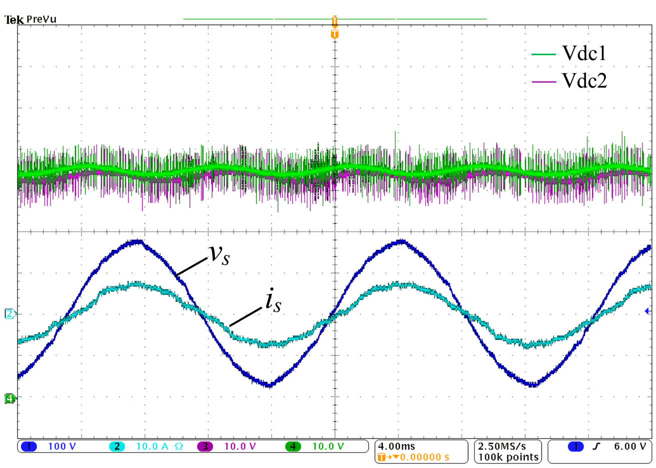


Fig. 12. Experimental results of individual MPPT.

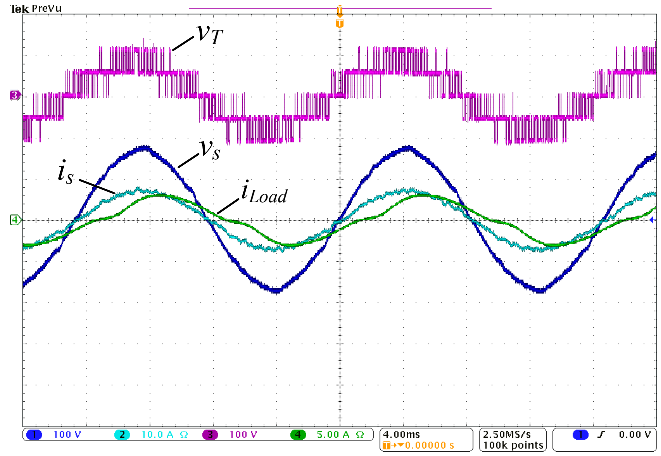


Fig. 13. Experimental voltage and current waveforms.

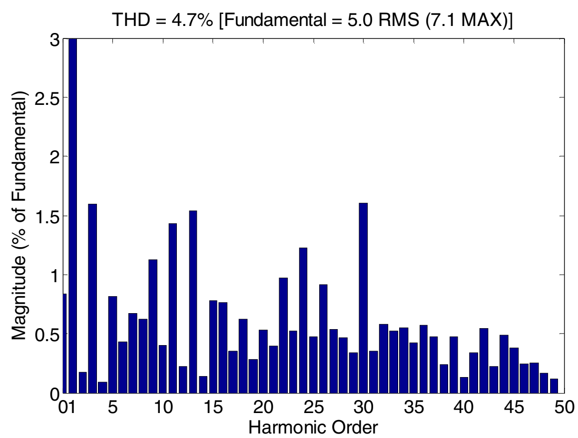


Fig. 14. THD of the grid current.

VI. CONCLUSIONS

In this paper, a single-phase modular cascaded H-bridge multilevel inverter for grid-connected PV system with nonactive power compensation has been presented. Individual MPPT control is realized to maximize the solar energy extraction of each PV string and improve the efficiency of the PV system. The nonactive power required by the local load is provided by the proposed system, which realizes the power factor correction and reduces distribution losses. Simulation and experimental results confirmed the proposed ideas.

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