Single-Phase Cascaded H-Bridge Multilevel Inverter with Nonactive Power Compensation for Grid-Connected Photovoltaic Generators

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***Abstract*—This paper presents a single-phase cascaded H-bridge multilevel inverter for a grid-connected photovoltaic (PV) system with nonactive power compensation. A generalized nonactive power theory is applied to generate the nonactive current reference. Within the inverter's capability, nonactive power required by the local load is provided to improve the grid power quality. To minimize harmonics and achieve zero error tracking, a hybrid controller composed of a proportional controller and a repetitive controller is applied to current control. A single-phase 11-level cascaded multilevel inverter is considered in both simulation and experimental tests. 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 many advantages such as no fuel costs, no pollution, no noise, and little maintenance. Solar photovoltaic panels have been among the fastest growing energy sources in the world, and the growth is mostly in grid-connected applications. In 2010, more than 78% of the global market was for grid-connected applications.

In grid-connected systems, the panels needed to reach the required power levels are usually arranged in strings. The cascaded H-bridge multilevel inverter requires a separate 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 grid-connected PV applications [1-3]. The multilevel inverter also presents the advantages of reducing the device voltage stress, reducing output filters, and being high efficiency [4].

In this paper, 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 maintain good power quality in the grid. In current control, a hybrid controller is designed to minimize harmonics and achieve zero error tracking. Finally, an 11-level cascaded H-bridge inverter is considered in both simulation and experimental tests. Simulation and experimental results are given.

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.

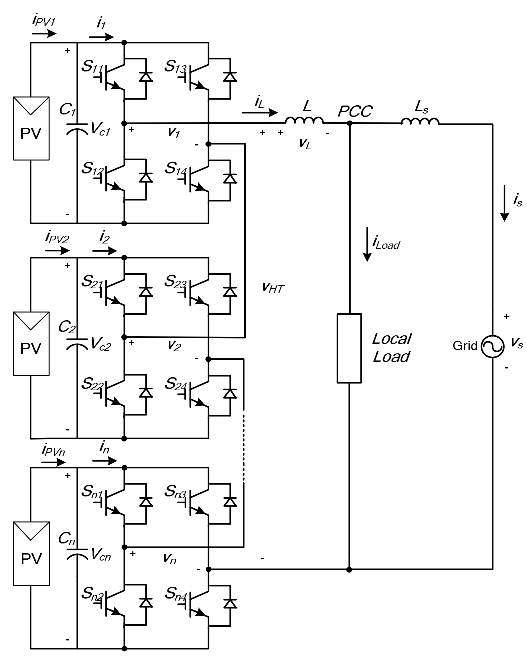


Fig. 1. Topology for the grid-connected system.

By different combinations of the four switches in each H-bridge, three output voltage levels can be generated, $-v_c$, 0, or $+v_c$. 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 generated current, reducing the output filters.

As shown in Fig. 1, the cascaded multilevel inverter is connected to the grid through a L filter, which is used to reduce the switching harmonics. 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. *Control Scheme*

The control scheme is based on the classical scheme for the control of a single H-bridge converter connected to the grid [5-7]. To maximize the energy harvested from each string, a maximum power point tracking (MPPT) controller is added to generate the dc-link voltage reference. The proposed control scheme is shown in Fig. 2.

The sum of the dc-link voltages v_{c1} to v_{cn} 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 subsection. The current controller gives the modulation index of the cascaded multilevel inverter and 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 [8], [9]. The incremental conductance method has been used in this paper. It lends itself well to DSP control, which can easily keep track of previous values of voltage and current, and make all the decisions, as shown in Fig. 3.

B. *Generalized Nonactive Power Theory*

The generalized nonactive power theory [10] 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.

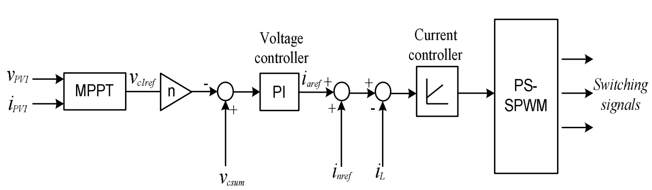


Fig. 2. Control scheme.

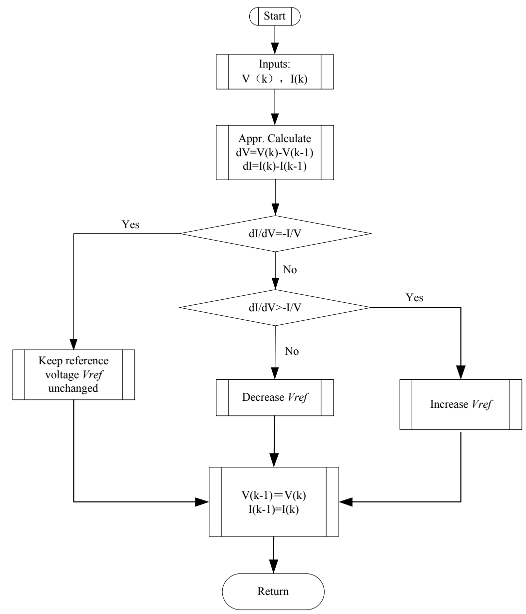


Fig. 3. Flowchart of the incremental conductance method.

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

$$P(t) = \frac{2}{T}\int_{t-\frac{T}{2}}^{t} v_{Load}(\tau) i_{Load}(\tau) d\tau \tag{1}$$

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

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

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

$$i_n(t) = i_{Load}(t) - i_a(t) \tag{3}$$

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 grid 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 by the multilevel inverter, which helps to improve the grid power quality and reduce the distribution circuit losses [11], [12].

C. *Current Loop*

In the current loop, a hybrid controller composed by a proportional controller and a repetitive controller is designed to restrain harmonics and achieve the zero error tracking of the current reference in the steady state. The

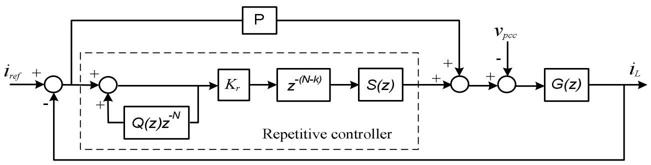


Fig. 4. Hybrid control scheme of the current loop.

repetitive controller can force periodic tracking error to approach zero asymptotically [13], but the dynamic response is slow. So the hybrid controller is applied, in which the proportional controller improves the dynamic response and the repetitive controller improves the accuracy in steady state. The hybrid control scheme of the current loop is shown in Fig. 4.

Considering the influence of the zero-order holder, the system plant is given by

$$G(z) = Z\left[\frac{1-e^{-Ts}}{s} \cdot \frac{1}{Ls+R}\right] = \frac{1-e^{-(R/L)T}}{R(z-e^{-(R/L)T})} \tag{4}$$

The repetitive controller is proposed as follows

$$G_{rc}(z) = \frac{K_r z^{-(N-k)} S(z)}{1-Q(z)z^{-N}} \tag{5}$$

where K_r is the repetitive control gain; N denotes the number of samples taken in one period of the reference current; k is the phase compensating parameter. The compensator *S(z)* is designed to let the amplitude - frequency characteristic of the system plant to have zero gain in the low-frequency band. *Q(z)* denotes the steady-state accuracy of the repetitive controller, and if *Q(z)* is equal to 1, the steady-state error would be zero. Usually, *Q(z)* is chosen as a constant close but less than 1 to ensure the stability of the system.

IV. RESULTS

Simulation and experimental tests are carried out to validate the proposed ideas. In both cases, an 11-level cascaded H-bridge inverter is considered. Each of the five H-bridges has its own 195 W PV panel connected as an independent source.

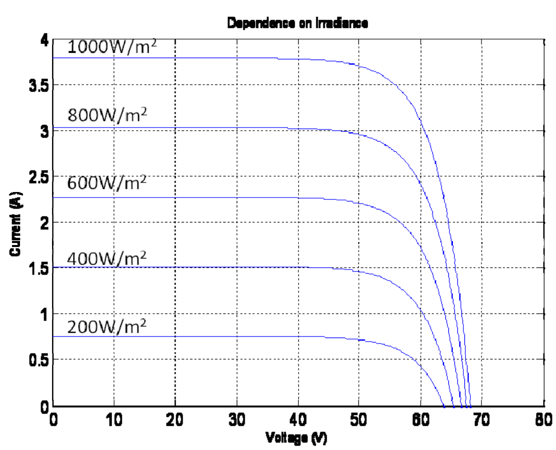


Fig. 5. *I-V* characteristic under different irradiance.

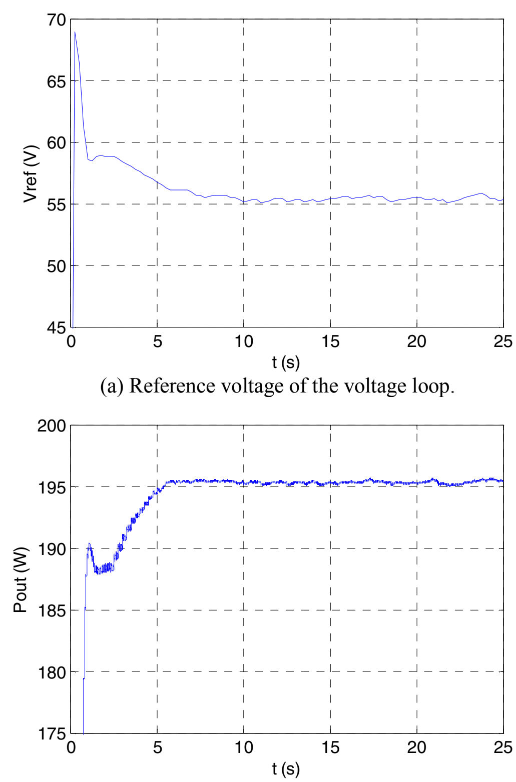
The PV panel is modeled according to the specification of the commercial PV panel from Sanyo, HIP-195BA19. The *I-V* characteristic of the panel obtained by simulation is shown in Fig. 5. The system parameters are shown in Table I.

The incremental conductance method is used to generate the dc-link voltage reference. As shown in Fig. 6, the reference dc-link voltage of the voltage loop is controlled to be 55.3 V, which is the maximum power voltage of the PV panel. So the output power of the PV panel can achieve 195 W.

The voltage and current waveforms of the grid and load are shown in Fig. 7. It can be seen that the load voltage is tracking the grid voltage. The load current is lagging the voltage, however, even if the grid is sending power to the

TABLE I. SYSTEM PARAMETERS

Parameters	Value
DC-link capacitor	2300 μF
Connection inductor L	5 mH
Load inductor	20 mH
Load resistor	20 ohm
Grid inductor	3 mH
Grid resistor	0.2 ohm
Grid rated RMS voltage	120 V



(a) Reference voltage of the voltage loop.

(b) Output power of the PV panel.

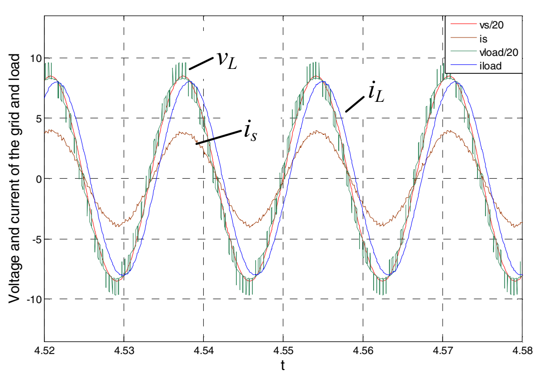
Fig. 6. Simulation results of MPPT control (S=1000 W/m², T=25 ˚C).

local load or receiving power from the PV system, the grid current has the same phase as the voltage, which means the grid has unity power factor. Sending or receiving power of the grid depends on the operation conditions of the PV panels. For example, when the PV panels are operated under irradiance S=1000 W/m^2, temperature T=25 ˚C, the PV system can provide enough power to the local load and send the extra power to the grid, as shown in Fig. 7 (a).

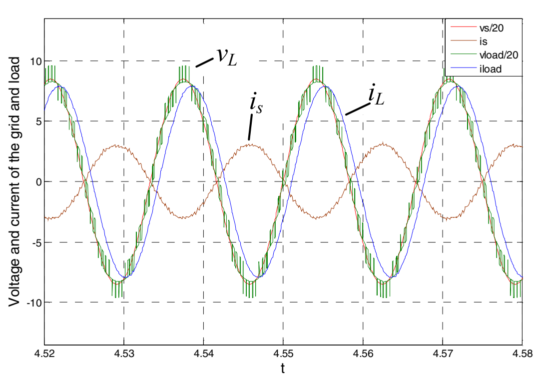
Fig. 8 shows the THD of the inverter output voltage, the load voltage and the grid current when the PV is operated under irradiance S=1000 W/m^2. Due to the cascaded H-bridge multilevel inverter, the THD is low even without any filter. The high order harmonics could be easily eliminated by adding a small filter, and the THD can be further reduced.

A 1 kW hardware prototype has been built in the laboratory. The MOSFET IRFSL4127 is selected as inverter switches operating at 250 Hz. The control signals to the H-bridge inverters are sent by the dSPACE ds1103 controller. Fig. 9 shows the experimental solar panels and the 11-level cascaded multilevel inverter.

The experimental results are presented in Fig. 10. The experimental results also show that the grid current has the same phase as the grid voltage and has unity power factor. In this case, the grid receives power from the PV system.

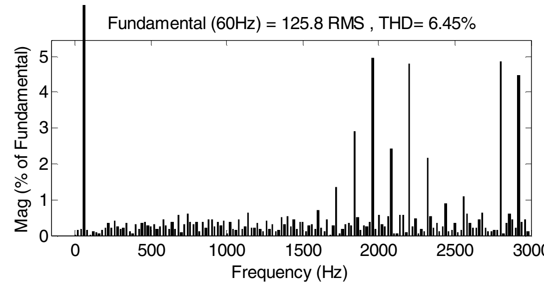


(a) S=1000 W/m^2, grid receives power from PV.

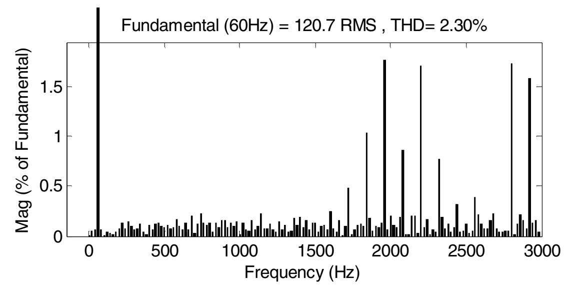


(b) S=400 W/m^2, local load receives power from grid.

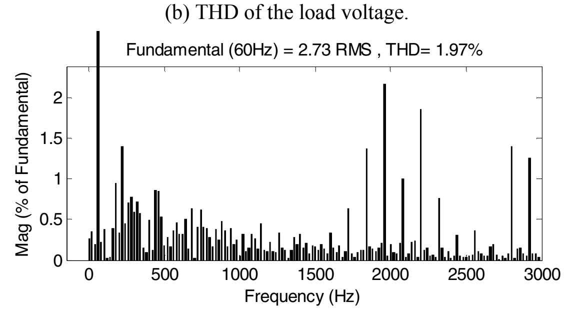
Fig. 7. Voltage and current waveforms of grid and load (T=25 ˚C).



(a) THD of the inverter output voltage.



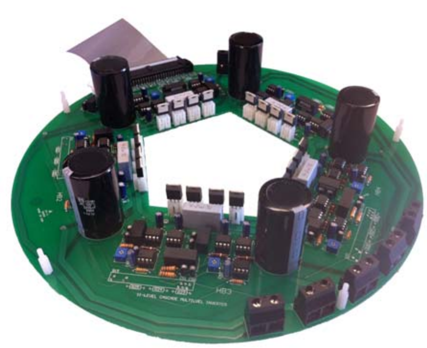
(b) THD of the load voltage.



(c) THD of the grid current.

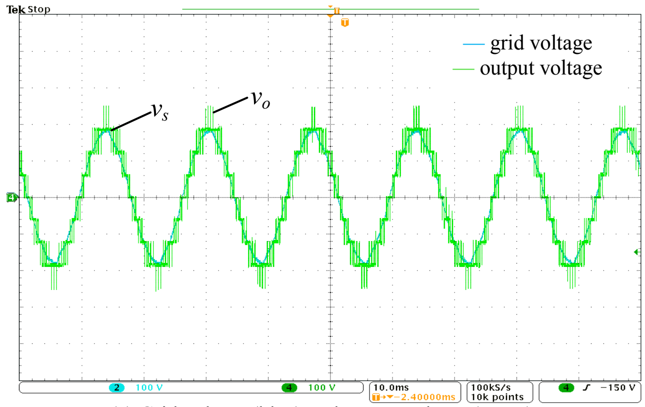
Fig. 8. THD of the voltage and current (S=1000 W/m^2, T=25 ˚C).

(a) Solar panels

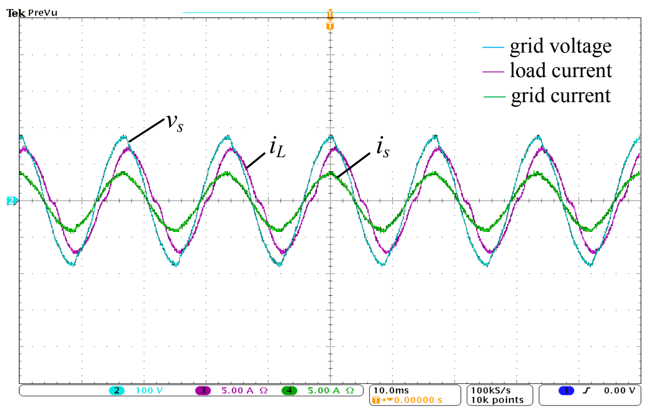


(b) Single-phase 11-level cascaded multilevel inverter.

Fig. 9. Experimental prototype.



(a) Grid voltage (blue) and output voltage (green).



(b) Grid voltage (blue), load current (purple) and grid current (green).

Fig. 10. Experimental voltage and current waveforms of grid and load.

V. CONCLUSIONS

In this paper, a single-phase cascaded H-bridge multilevel inverter for grid-connected PV system with nonactive power compensation has been presented. The nonactive power required by the local load is provided by the proposed system, which improves the grid power quality. A hybrid controller is applied to current control to restrain harmonics and achieve zero error tracking. Even without output filters, the THD of the load voltage and grid current are low. The simulation and experimental results confirmed the proposed ideas.

ACKNOWLEDGMENT

This work was supported by Stanford University's Global Climate and Energy Project (GCEP), which addresses grand challenges of this century.

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