A Hybrid CHB Multilevel Inverter with Supercapacitor Energy Storage for Grid-Connected Photovoltaic Systems

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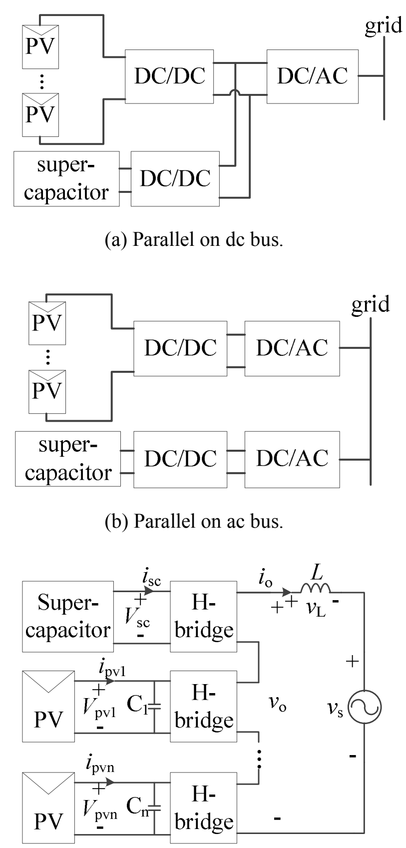
***Abstract*—This paper presents a single-phase cascaded H-bridge multilevel photovoltaic inverter containing a special supercapacitor cell. The cascaded H-bridge multilevel topology enables independent DC voltage control for each PV panel or string to meet the requirements of distributed maximum power point tracking, which reduces the efficiency loss caused by panel mismatch and unequal sheltering. But as the total power of distributed grid-connected photovoltaic inverter increases, the power fluctuation brought by those photovoltaic systems will become serious and even affect the stability of the grid. To alleviate this problem, a supercapacitor cell is added to the inverter. It not only smooths the PV inverter's output power fluctuation, but also increases the inverter's output level. For the coordination of these two kinds of cells, a control strategy is proposed, in which all cascaded PV cells only output active power, and the supercapacitor cell undertakes the reactive active power and compensates the active power fluctuations. Experimental results are presented to verify the feasibility of the proposed approach. The fluctuations in the output power are effectively smoothed, and the inverter gets unity power factor.**

***Keywords*—photovoltaic inverter; multilevel; cascaded converter; supercapacitor**

I. INTRODUCTION

Cascaded H-bridge (CHB) inverter is considered a promising solution for grid-connected photovoltaic (PV) system, because it can shorten the string of PV module, and outputs high voltage with multi levels through a one-stage conversion [1], [2]. CHB PV inverter intends to maximize the solar energy extraction by adopting independent maximum power point tracking (MPPT) control for each PV cell to avoid the efficiency degradation due to unequal irradiation and panel parameter dispersion, or dust on the panel surface [3]. So far, several methods have been proposed to realize independent MPPT control [1], [2], [4], [5].

But the power fluctuation problem of PV systems cannot be solved by the topology itself. As the number of grid-connected PV systems increases, the impact of power fluctuation on the grid can become a serious problem. Therefore, energy storage components such as various batteries and supercapacitors are put into PV systems [6]-[8]. In these schemes, as shown in Fig. 1 (a) and (b), batteries or supercapacitors are connected either to the dc bus of a PV inverter via a dc/dc converter, or to a dc/ac converter working as a standalone power compensator.



(a) Parallel on dc bus.

(b) Parallel on ac bus.

(c) Hybrid cascaded.

Fig. 1 Structures of PV systems with supercapacitor.

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Since supercapacitor is more adaptive to fast charging and discharging operation than batteries, it seems to be more suitable for use in such systems. In the system depicted in Fig. 1 (a), all PV modules are connected in series to form a long string, which helps to get a relatively high dc voltage, but suffers efficiency loss because it can only use a unified MPPT control. If a CHB PV inverter applies supercapacitors for each PV cell, the topology will become too complex and expensive.

Compared to Fig. 1 (a), the system in Fig. 1 (b) uses an extra dc-ac converter for the supercapacitor. This two-stage conversion for the supercapacitor will reduce efficiency. In addition, the dc-ac converter should use high-voltage devices, and has only a few output levels and large amount of harmonics. So Fig. 1 (b) is not a satisfactory solution either.

This paper presents a scheme connecting the supercapacitor in series to the ac output side of the inverter through an H-bridge inverter, as shown in Fig.1(c). In this scheme, the supercapacitor connects to the system with only one H-bridge inverter, and all the H-bridges use low-voltage devices. The whole inverter has multi output levels, and the supercapacitor cell further increases the number of levels, so the output filter is small. To make the PV cells and the supercapacitor cell work coordinately, a special control strategy developed on the basis of the control method of a regular CHB PV inverter with distributed MPPT is presented in section III. Experimental results are given out in section IV.

II. PROPOSED TOPOLOGY

As depicted in Fig. 1 (c), this proposed hybrid cascaded PV inverter consists of n PV cells and one supercapacitor (SC) cell. Each PV cell has one PV panel (or a short PV string) and a filter capacitor. In the SC cell, a SC stack connects to the H-bridge directly.

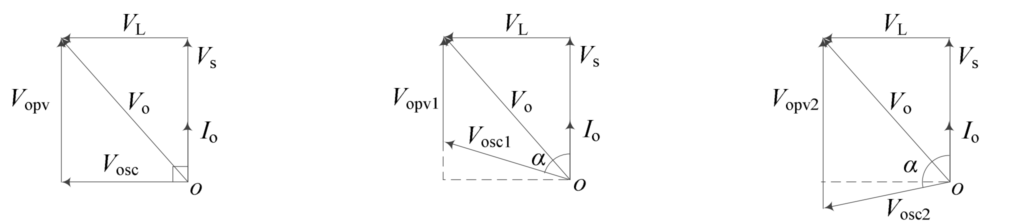
Because every cell has three output levels ($-v_{dc}$, 0 and $+v_{dc}$), n+1 cells can provide 2n+3 levels. Obviously, more cells increase the number of output levels, which will bring less harmonics and a smaller filter inductor L. On the other hand, the cells can use low-rated power semiconductors which cost low.

In this topology, the SC cell is assigned to output reactive power and smooth active power fluctuations within its capacity range. Obviously, the capacity of supercapacitor directly determines the effect of power compensation. Compensation strategies can be designed in different ways according to different principles. The focus of this paper is to discuss and verify the feasibility of the scheme.

It should be noted that since the supercapacitor will charge or discharge when the total power of PV cells is excessive or insufficient, the dc voltage of SC cell may always vary in a wide range. So the dc voltage of SC cell and PV cells are not the same and even quite different.

III. CONTROL SCHEME

The coordinative working mode of the PV cells and the SC cell can be depicted by the phasor diagrams in Fig. 2. The inverter's output voltage V_o is synthesized by all PV cells' output voltage V_{opv} and the SC cell's output voltage V_{osc}. The voltage on the inductor L V_L is obtained by the difference between V_o and the grid voltage V_s. If V_L is perpendicular to V_s, then the output current I_o is parallel to V_s. So the inverter gets a unity power factor.



(a) SC cell only outputs reactive power. (b) SC cell compensates active power. (c) SC cell absorbs active power.

Fig. 2 Phasor diagram of the synthesizing of the inverter's output voltage.

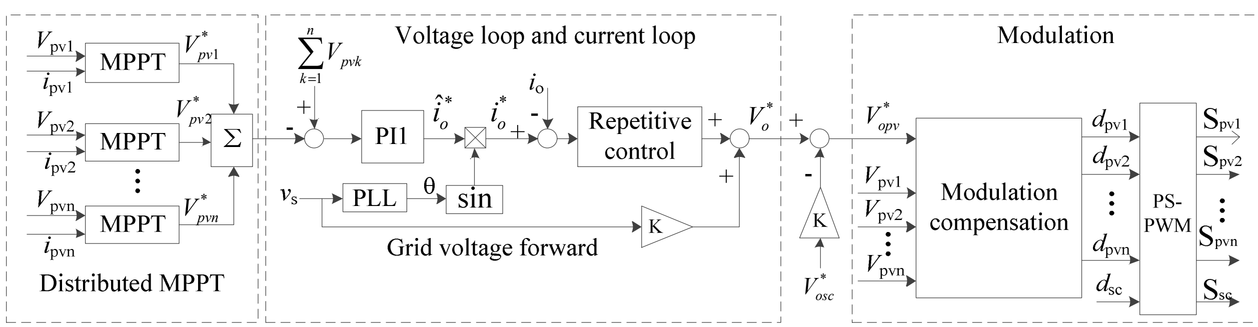


Fig. 3 Control scheme for the proposed single-phase hybrid CHB PV inverter

When the PV cells provide enough active power and the SC does not need to charge or discharge, as in Fig. 2(a), the controller of the inverter makes V_{osc} equal V_L. In this state, the SC cell only provides the reactive power consumed by the inductor L.

When the power of PV cells is insufficient or over the rated level, causing the output voltage of all PV cells V_{opv} turn into V_{opv1} or V_{opv2}, as in Fig. 2(b) and (c), the SC cell adjusts its output voltage accordingly to provide or absorb the active power difference.

A. Total Control Scheme

Fig. 3 shows the total control scheme which is based on the classic voltage and current loop control scheme of a single-phase inverter.

Each PV cell has an independent MPPT module. The dc voltage references generated by those MPPT modules are summed to be the reference of the dc voltage loop, and a PI controller is used. A repetitive controller is used in the current loop [9], and a grid voltage feedforward is added to eliminate the impact of grid voltage fluctuation. θ is the phase of the grid voltage obtained by a phase lock loop (PLL). The SC cell's output reference V_{osc}^* is subtracted from the total output reference V_o^* to obtain the PV cells' total output reference V_{opv}^*. To make the dc voltage of every PV cell follows the reference value generated by its own MTTP module, a modulation compensation module is used to adjust the output voltage reference of each PV cell according to its dc voltage. The generation of V_{osc}^* and the modulation compensation module are explained in part B and C.

B. Control of SC Cell

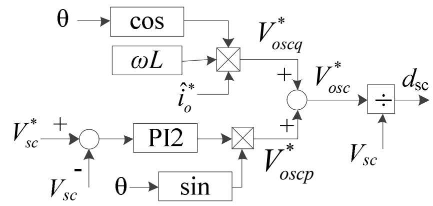
The SC cell has two working states, static state and compensating state. The generation schemes of V_{osc}^* in these two states are depicted in Fig. 4. In static state, PV cells' power is sufficient and stable, and the SC cell outputs the voltage drop on the inductor V_L and absorbs a small amount of active power to offset its internal loss. In compensating state, besides V_L, the SC cell outputs or absorbs active power according to the difference between all PV panels' power and the rated power P_{pv}^*. The reactive component of V_{osc}^* is calculated by

$$V_{oscq}^* = \omega L \hat{i}_o^* \cos\theta \tag{1}$$

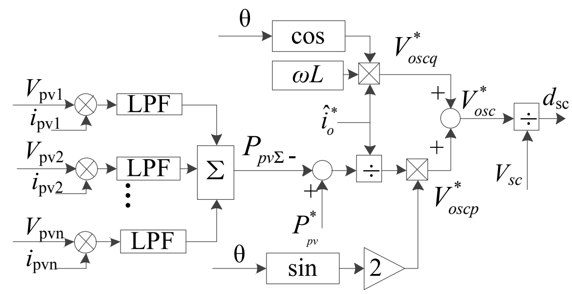
where $\hat{i}_o^*$ is the amplitude of output current reference. In compensating state, the active component of V_{osc}^* is calculated by

$$V_{oscp}^* = \sqrt{2}\frac{\left(P_{pv}^* - P_{pv\Sigma}\right)}{\hat{i}_o^*/\sqrt{2}}\sin\theta = \frac{2\left(P_{pv}^* - P_{pv\Sigma}\right)}{\hat{i}_o^*}\sin\theta \tag{2}$$

where $P_{pv\Sigma}$ is the sum of all PV panels' power.



(a) Static state



(b) Compensating state

Fig. 4 Generation of SC cell's output voltage reference.

For simplicity, a simple criterion is used to determine the state in this paper. If $P_{pv\Sigma}$ deviates from P_{pv}^* of more than 5%, then the SC cell turns from static state to compensating state. Certainly, the extent of power compensating should be limited by the capacity of the SC. So the practical criterion may be designed more complex. But this does not affect the verification of the operating principle of the SC cell in this paper.

C. Modulation Compensation

The modulation compensation method is derived from [10] to ensure the dc voltage of PV cells follow their MPPTs. As in Fig. 5, a PI controller is used to regulate the normalized dc voltage error, and its output, multiplied by $\sin\theta$, is added to the total PV cell output reference V_{opv}^* to generate modulation index for each cell.

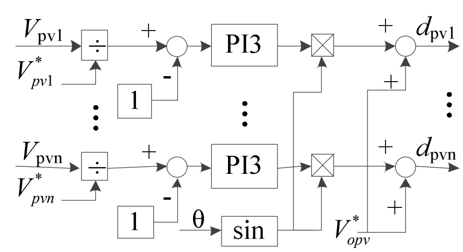


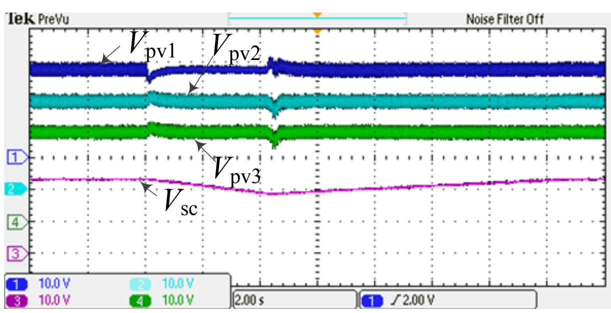
Fig. 5 Modulation compensation for PV cells.

IV. Experimental Results

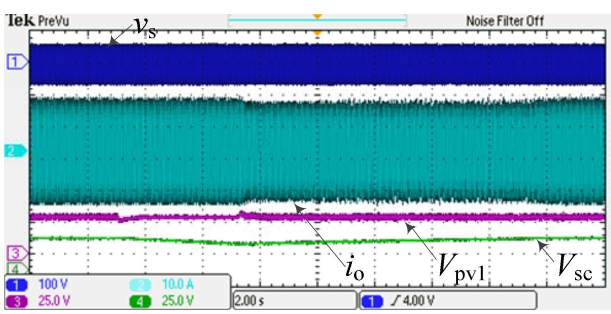
An experimental platform of the proposed inverter containing three PV cells and one SC cell has been built. Its controller consists of a DSP (TMS320F2812) and an FPGA (EP4CE115). Three 280-W PV panels and a 32V/4F SC stack are connected to the inverter. The operating voltage of the SC cell is set to 24V. The MOSFET IPB042N10N is used as inverter switches operating at 10 kHz. The inverter connects to the grid via a 40V/220V transformer. In the experiment, the first panel is partly covered by a piece of paper for about 4 s, and then the paper is taken away.

Fig. 6(a) shows the dc voltages of the four cells. The dc voltage of the first panel becomes lower and then rises up. The other two panels keep their MPPs unchanged except some transients. When the first panel is partly covered, controller of the inverter detects the total power decline of more than 5% of the original value. Then the SC cell quickly turns to compensating state, and its dc voltage falls. In Fig. 6(b), the output current keeps constant during this state. When the first panel recovers, the SC cell returns to static state and starts charging with a steady speed, resulting in a little reduction in the output current in Fig. 6(b).

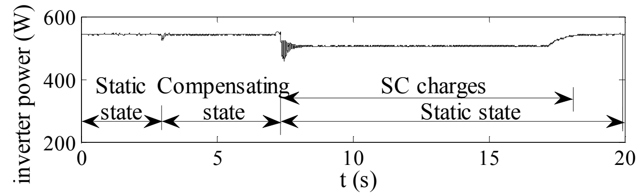
Fig. 6(c) depicts the power injected to the grid calculated with the data of v_s and i_o recorded in Fig. 6(b). It can be seen that during the compensating state, the output power of the inverter does not change obviously except the initial transient. Fig. 6 (d) and (e) show the power factor and the output voltage waveform of the inverter.



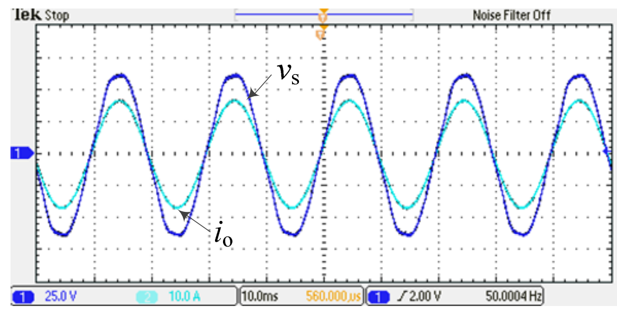
(a) DC voltages of PV cells and SC cell



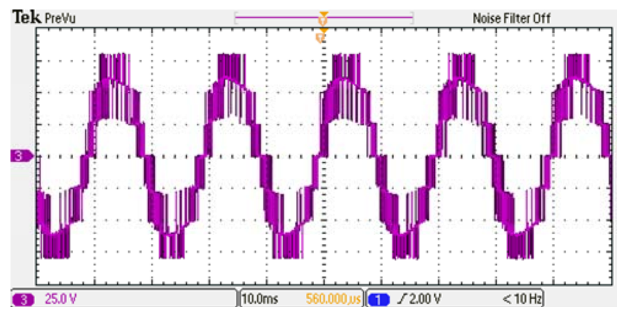
(b) Grid voltage and output current



(c) Power injected to the grid



(d) Phase of grid voltage and output current



(e) Output voltage of the inverter

Fig. 6 Experimental waveforms.

V. CONCLUSIONS

The proposed hybrid CHB PV inverter for grid-connected applications puts the supercapacitor in a special cell which is cascaded with PV cells on ac side in series. It uses the only one SC cell to compensate the power fluctuation of all PV modules, and only employs low-voltage devices. It has small d*u*/d*t* and needs small output filter. Its control scheme applies independent MPPT control and modulation compensation for each PV cell, and changes the SC cell's output state according to the power of the PV cells. When the PV power fluctuates, the SC cell outputs or absorbs active power. When the PV power is stable and enough, the SC cell just keeps its own dc voltage stable. No matter which state the SC cell is in, it always provides the reactive power consumed by the filter inductor, thus ensuring the whole inverter has a unity power factor. The experimental results verify that with this control scheme, the power fluctuations of the cascaded PV inverter can be effectively smoothed under the condition of sufficient capacity of the supercapacitor.

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