

# A Synergistic Modulation Method for Hybrid Cascaded Photovoltaic Inverter with Supercapacitor

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**Abstract**—A hybrid cascaded photovoltaic (PV) inverter with supercapacitor is proposed, and a synergistic modulation method adapted to the operation principle of the inverter is presented. This inverter contains a supercapacitor cell and several PV cells. The supercapacitor cell uses specific harmonic elimination (SHE) technique to eliminate a part of the low-frequency harmonics in its output voltage, while the PV cells adopt carrier phase-shift PWM (PS-PWM). And a compensation component calculated from the rest low-frequency harmonics generated by supercapacitor cell is added to the modulation index of PV cells, to further reduce the harmonics in the total output voltage. Experimental results show that compared with regular PS-PWM method, the proposed modulation method has less low-frequency harmonics and lower THD when the output voltages and dc voltages of the two types of cells are quite different.

**Keywords**—photovoltaic inverter; hybrid cascaded converter; selected harmonic elimination; phase-shift PWM

## I. INTRODUCTION

Adopting cascaded H-bridge inverter in photovoltaic (PV) systems can shorten the string length of photovoltaic modules, and use independent maximum power point tracking (MPPT) control in each cascaded cell to improve power generation efficiency [1]-[4]. This also enables the use of low-voltage devices in a high-voltage grid-connected PV system. Meanwhile, by using carrier-based phase-shift PWM (PS-PWM) modulation method, the cascaded inverter greatly increases its equivalent switching frequency and effectively reduces low-frequency harmonics [5]. Thus, the cascaded PV inverter has good output waveform and requires smaller size output filter.

Due to the influence of environmental factors, the output power of PV modules fluctuates greatly [6]. Usually in distributed PV systems, the issue of energy storage is not considered because of cost. As the number of grid-connected PV systems increases, the impact of power fluctuation on the grid can become serious and even impact the stability of the grid. Therefore, energy storage components such as batteries and supercapacitors are put into PV systems [7-9]. In these schemes, batteries or supercapacitors are connected either to the dc bus of a PV inverter by a dc/dc converter, or to a dc/ac

converter working as a standalone power compensator. Because supercapacitor is able to charge and discharge with fast speed, so it is more preferred than batteries in the situation of power fluctuation suppression.

But the two-stage conversion will lower the efficiency. And it is quite expensive complex to place a supercapacitor in each cascaded PV cell. If the supercapacitor connects to the grid via an independent dc-ac converter, this converter will have only a few output levels and large amount of low-frequency harmonics.

This paper introduces an inverter putting a supercapacitor in an independent cell which connects with PV cells in series on ac side of the inverter, as shown in Fig.1.

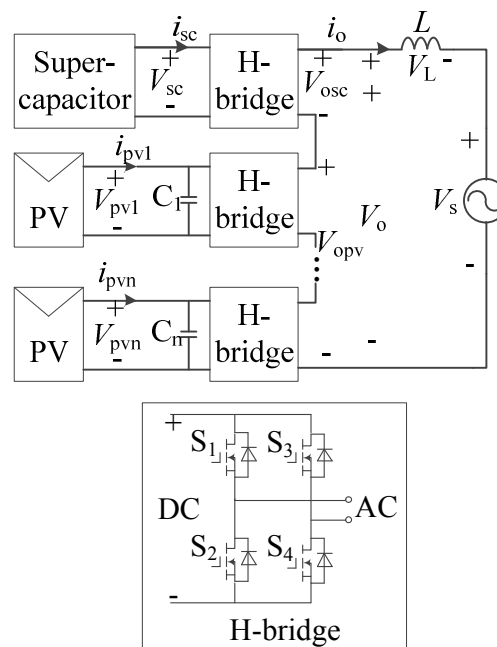


Fig. 1 Structure of hybrid cascaded PV system with supercapacitor.

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The topology and operation principle of the inverter are described in section II. A control scheme for this inverter is presented in [10]. A synergistic modulation method suitable for the structure and its operation principle is proposed in section III. This modulation method uses different modulation technique in the two types of cells, and makes the PV cells work like a harmonic compensator for the low-frequency harmonics generated by the supercapacitor cell. Finally, experiments are carried out on a Hardware-In-the-Loop test bed. Experimental results given in section IV show the different output waveforms of the proposed synergistic modulation method and the regular unified PS-PWM modulation.

## II. TOPOLOGY AND OPERATION PRINCIPLE

As shown in Fig. 1, the hybrid cascaded PV inverter consists of one supercapacitor (SC) cell,  $n$  PV cells and an output filter inductor  $L$ . Each PV cell has one PV panel (or a short PV module string) and a filter capacitor. In the SC cell, an SC stack connects to the H-bridge directly, and its dc voltage may be different from that of the PV cells. Obviously, with the SC cell, the number of output levels is increased. In addition, all 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 of PV cells within its capacity range. The operation principle of the inverter can be summarized in three cooperative working modes of the two types of cells, depicted by the phasor diagrams in Fig. 2.

The output voltage of the inverter  $V_o$  is synthesized by all PV cells' output voltage  $V_{opv}$  and the SC cell's output voltage  $V_{osc}$ . The voltage drop on the inductor  $V_L$  is determined by the difference between  $V_o$  and the grid voltage  $V_s$ . When  $V_L$  is perpendicular to  $V_s$ , the output current  $I_o$  is parallel to  $V_s$ . Thus the inverter gets unity power factor. When the PV cells provide enough active power, as in Fig. 2(a), the SC cell only outputs the reactive power on the inductor  $L$ , and  $V_{osc}$  equals  $V_L$ . When the power of PV cells changes abruptly, and  $V_{opv}$  becomes  $V_{opv1}$  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.

It can be seen from Fig. 2 that no matter in which working mode, the output voltages of the two types of cells have different amplitudes and phases. In addition, since the SC stack may charge or discharge at any time as the power of the PV

module changes, the dc voltage of the SC cell may change in a wide range. So the dc voltages of the SC cell and PV cells are also different.

## III. SYNERGISTIC MODULATION METHOD

Since the dc voltages and output voltages of the two types of cells are quite different, the regular modulation method for cascaded inverter that only employs carrier-based PS-PWM modulation for all cells is not suitable for this inverter [11]. This is because that the precondition of low-order harmonic cancellation of PS-PWM is that all cascaded cells have the same dc voltages and the same output voltages. When this precondition is not met, low-order harmonics will increase substantially.

The proposed method is that the SC cell uses specific harmonic elimination (SHE) technique to eliminate some of the low-frequency harmonics in its output voltage, while the PV cells adopt carrier-based PS-PWM. And the PV cells compensate the rest low-frequency harmonics generated by SC cell. Even though the dc voltages of all PV cells may also vary a little as independent MPPTs are applied for every PV cell, the difference among them are small, and the number of PV cells is relatively large, so this will not affect the total harmonics too much.

### A. SHE Modulation of the SC Cell

For simplicity, taking the example of an H-bridge that uses SHE modulation and has three independent switching angles. According to the principle of SHE, when outputs a voltage waveform as shown in Fig. 3, the output waveform can be decomposed into the sum of the fundamental and a series of harmonics as following.

$$f(t) = \sum_{k=1,3,5}^{\infty} V_k \sin(k\omega t) \quad (1)$$

$$V_k = -\frac{4V_{dc}}{n\pi} \left[ 1 + 2 \sum_{l=1}^3 (-1)^l \cos(k\alpha_l) \right] \quad (2)$$

Since the H-bridge has three independent switching angles, three equations can be got as in Equ. (3). The first one is to meet the fundamental of the output reference. Then the rest two can be used to force two designated harmonics to be eliminated.

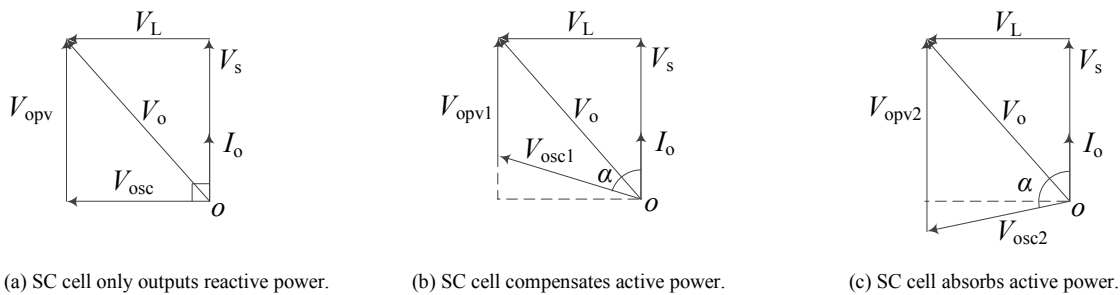


Fig. 2 Phasor diagram of the inverter's output voltage.

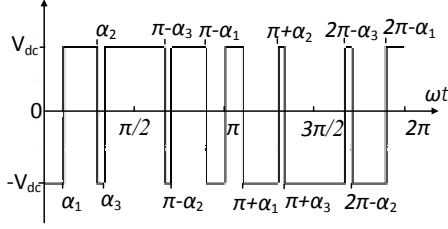


Fig. 3 Output waveform of an H-bridge using SHE.

$$\begin{aligned} V_1 &= \frac{4V_{dc}}{\pi} [2(\cos\alpha_1 - \cos\alpha_2 + \cos\alpha_3) - 1] = m \times V_{dc} \\ V_3 &= \frac{4V_{dc}}{3\pi} [2(\cos 3\alpha_1 - \cos 3\alpha_2 + \cos 3\alpha_3) - 1] = 0 \\ V_5 &= \frac{4V_{dc}}{5\pi} [2(\cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3) - 1] = 0 \end{aligned} \quad (3)$$

In a single-phase inverter, the 3<sup>rd</sup> and 5<sup>th</sup> order harmonics are the two lowest orders. So this two harmonics are chosen to be eliminated. If the method is applied to a three-phase inverter, then the 3<sup>rd</sup>, 9<sup>th</sup> order harmonics, and so on are automatically offset. So the 5<sup>th</sup> and 7<sup>th</sup> order harmonics can be selected.

Given a certain modulation index of the H-bridge  $m$ , the three switching angles can be solved by Equ. (3). Obviously, the switching angles change with the modulation index  $m$  varying in the range of  $[0, 1]$ , as depicted in Fig. 4. By using the solutions provided by Fig. 4, the 3<sup>rd</sup> and 5<sup>th</sup> harmonics can be eliminated while the fundamental output reference is satisfied.

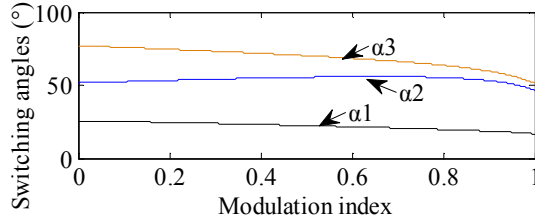


Fig. 4 Switching angles of SHE.

The more the number of independent switching angles, the more harmonics can be eliminated. But the difficulty of solving increases greatly caused by the increase of the number of equations. For the rest higher order harmonics, their amplitude and instantaneous values can be calculated according to equation (1) and (2). By summing the instantaneous values of all the specified harmonics that need to be dealt with, the instantaneous harmonic value to be compensated by PV cells, which is called  $h$ , is obtained.

$$h(t) = - \sum_{k=7,9,\dots} \frac{4V_{dc}}{k\pi} \left[ 1 + 2 \sum_{l=1}^3 (-1)^l \cos(k\alpha_l) \right] \sin(k\omega t) \quad (4)$$

#### B. PS-PWM and Harmonic Compensating of the PV Cells

Suppose that  $m_{pv}$  is the original modulation index of PV

cells generated by the controller, the final modulation index is

$$m'_{pv} = m_{pv} - h / \sum V_{pvn} \quad (5)$$

where  $\sum V_{pvn}$  is the sum of dc voltages of all PV cells. If the range of the triangular carriers of PV cells in PS-PWM modulation is  $[-1, 1]$ , then  $|m'_{pv}| < 1$  should be ensured to avoid saturation.

Fig. 5 depicts the calculation results of the maximum value of  $h/V_{dc}$  with different modulation indices of the SC cell. It seems that the limit of  $m_{pv}$  can be determined by  $1 - h_{\max} / \sum V_{pvn}$ . Actually, because of the phase difference between output reference value of the PV cells and the total harmonic value to be compensated, they may not reach their peak values simultaneously. But this limit calculation will still help to keep some safe margin and determine the proper ratio of  $V_{dc}$  to  $\sum V_{pvn}$ , or in other words, the proper number ratio of the SC cell to the PV cells.

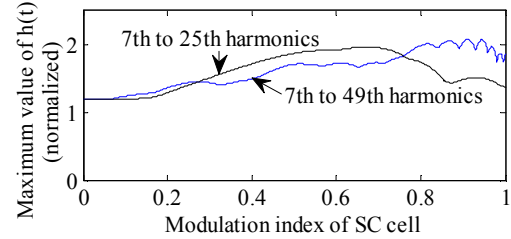


Fig. 5 Maximum amplitude of  $h/V_{dc}$ .

If the switching frequency of a single PV cell is  $f$ , PS-PWM modulation can raise the equivalent switching frequency of an  $n$ -cell inverter to  $2nf$ . According to Shannon sampling theorem, the harmonics of frequencies below  $nf$  can be compensated. When the above two conditions about modulation index and the switching frequency are met simultaneously, the specified harmonics generated by the SC cell can be compensated by the PV cells.

Since the switching frequency of the SC cell is much lower than  $nf$ , the amount of the high-frequency harmonics in the SC cell output voltage is very little. Hence the majority of the harmonics generated by the SC cell can be compensated. Thus on the whole, the low-frequency harmonics of the inverter can be eliminated to a very low level.

Meanwhile, because the switching angles and the waves of the harmonics can be calculated offline, so this algorithm does not add too much computation to the controller by using look-up tables.

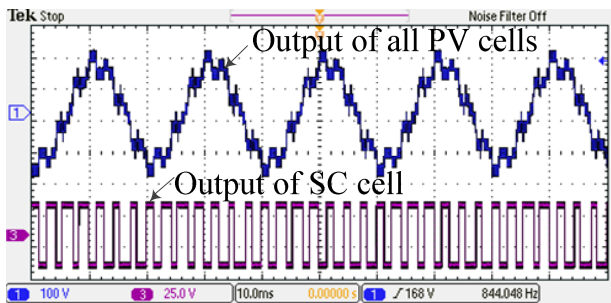
#### IV. EXPERIMENTAL RESULTS

A Hardware-In-the-Loop (HIL) test bed has been built with a real-time simulator OP5600 produced by OPAL-RT and a digital controller consisting of a DSP (TMS320F2812) and an FPGA (EP4CE115). An inverter containing seven PV cells and one SC cell was simulated in the simulator OP5600. The

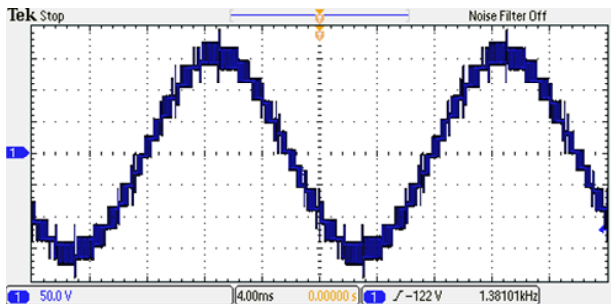
algorithm was developed in the digital controller. The controller outputs PWM signals to the simulator OP5600, and collects analog data from the analog output channels of OP5600.

The dc voltages of the PV cells and the SC cell are respectively 28V and 24V. The PWM switching frequency of the H-bridges is 1 kHz. In the experiments, the modulation indices of PV cells and SC cell are 0.794 and 0.33 respectively, and the phase difference of their output voltages is 90°. Odd harmonics from 7<sup>th</sup> to 49<sup>th</sup> order in the output of SC cell are compensated.

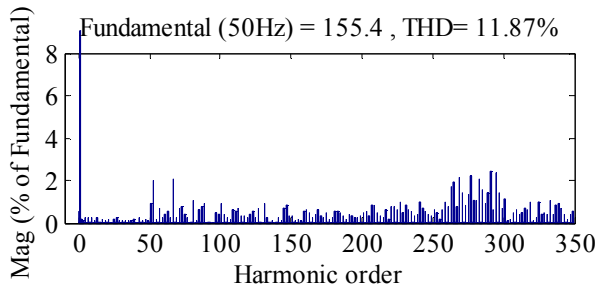
Fig. 6(a) shows the output of all the PV cells using PS-PWM and the output of the SC cell using SHE. The phase shift among the PV cell carriers is  $180^\circ/(2 \times 7)$ . The inverter's output waveform and its spectrum are in Fig. 6(b) and (c). Harmonics below the 50<sup>th</sup> order are all eliminated, and the THD is 11.87%.



(a) Output voltages of PV cells and SC cell



(b) Synthesized output voltage of the inverter



(c) FFT analysis of the output voltage

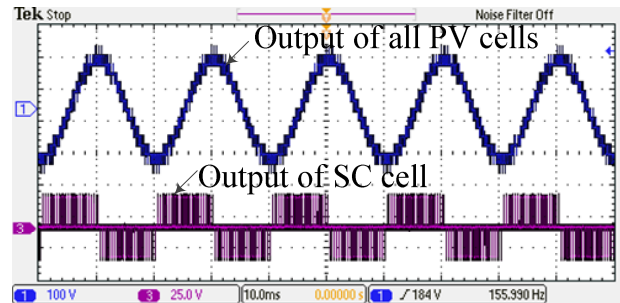
Fig. 6 Waveforms of the proposed method.

Fig. 7 shows the results when all cells use unified PS-PWM.

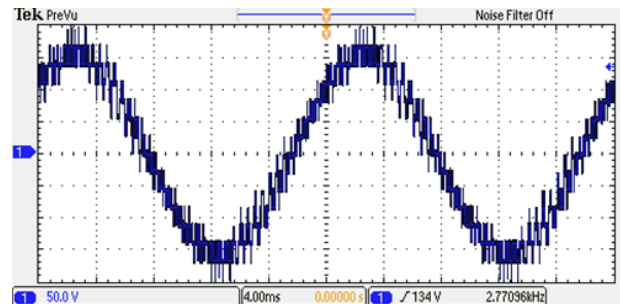
The phase shift among all the cell carriers is  $180^\circ/[2 \times (7+1)]$ . The THD is 16.55%, higher than that of the proposed modulation method. It can be seen in Fig. 7(c) that harmonics around the 40<sup>th</sup> order are big and this frequency is exactly 2 times the switching frequency of a single H-bridge. This is caused by the inconsistency of the output voltages of the two types of cells, and is inevitable.

Obviously, the switching frequency of SC cell in Fig. 7(a) is much higher than Fig. 6(a), so the switching loss of unified PS-PWM is higher than the proposed modulation method.

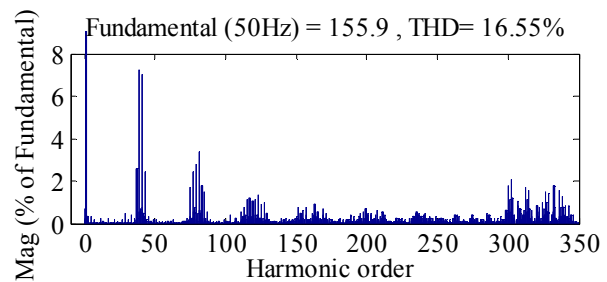
If the range of harmonics to be compensated is extended to higher than 50, then the amount of low-frequency harmonics will be further reduced. For the unified PS-PWM, the switching frequency of all H-bridges should be raised to reduce low-frequency harmonics, which will lead to an increase of switching loss.



(a) Output voltages of PV cells and SC cell



(b) Output voltage of the inverter



(c) FFT analysis of the output voltage

Fig. 7 Waveforms of PS-PWM.

It can be inferred from the algorithm of the synergistic modulation method that the differences in the output voltages

and dc voltages of the SC cell and the PV cells almost have no influence on the quality of the total output voltage waveform. Therefore, its power quality is stable and it is more suitable for the applications in which the dc voltage of the energy storage component changes in a wide range. On the contrary, the output harmonics of the unified PS-PWM will change with the differences of dc voltages and out references of the two types of cells. And if the number of cascaded cells is small, there will be a higher proportion of low-frequency harmonics.

## V. CONCLUSIONS

In the proposed hybrid CHB PV inverter for grid-connected applications, the PV cells and the SC cell work in a coordinative mode and output different voltages. Their dc voltages are also different. A synergistic modulation method suitable for this inverter is proposed. Selected harmonic elimination technique and PS-PWM are respectively adopted for the SC cell and the PV cells, and the PV cells compensate the specified low-frequency harmonics generated by the SC cell. The experimental results verify that the proposed modulation method has better waveform quality and fewer low-frequency harmonics than the regular unified PS-PWM. And it is more suitable for the applications in which the dc voltage of the energy storage component changes greatly.

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