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A Single Phase Bidirectional H6 Rectifier/Inverter with Switched Capacitor Compensator in PV Applications

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ABSTRACT: This paper proposes an advanced bidirectional technique for a selected H6 inverter topology with modified modulation strategy. For the H6 circuitry in both rectifier and inverter modes, excellent three level DM voltage feature is achieved, while leakage current issue is eliminated at the same time with improved modulation method. In addition to that the zero crossing distortions are minimized using a simple switched capacitor compensation scheme that avoids avoid input current being clamped to zero before the zero crossing of the input voltage and supply enough input current rising slope after zero crossing of the input voltage. Simulations and experimental results verify the proposed single phase bidirectional H6 rectifier/inverter technique with a switched capacitor compensator.

KEYWORDS: H6 inverter; rectifier; zero crossing distortion, switched capacitor compensator.

I. INTRODUCTION

High penetration installed renewable energies are playing more important roles in electric power system, which gradually change the existing utility grid with more power electronics features due to grid-connected converters[1]. In summer weekends, renewable energies already provide 100% of demand in Germany [2]. The fundamental operation codes for existing power grid are continuously modified for grid-tie inverters, especially for PV applications [3]. The grid codes are not only focusing on unilateral restrictions on leakage current safety, harmonic limits, and anti-islanding requirements, but also place great emphasis on faults ride- through ability, reactive power compensation capability, grid frequency stability, and so on[4]-[17].

Traditional AC grids have a hierarchical structure and designed radial, ignorant to energy feed-in in medium- and low-voltage distribution grids considering regional energy resources balance. However, future grids cannot ignore the energy feed-in in medium- and low-voltage distribution grids. Voltage violation problems caused by high-density distributed PVs are common in distribution grids, which restrict the penetration rate of PV installations. Central static var generator (SVG), or distributed PV inverters with reactive power compensation capability of their own could eliminate voltage exceeding specified limits. The former SVG approach is more suitable for central PV plants, while the latter one would lose the price subsidy based on active power generation.

From the viewpoint of regional energy resources balance, distributed PV installation with energy storage is an attractive solution for high penetration PV applications like that in micro-grids. With the promotion and development of electric vehicles, battery cost would decrease following the similar cost reduction curve of PV products that took place in the past 20 years. A boom in battery industry, and there would be an increase in solar energy storage system. However, at present, most classic transformer-less PV inverters such as H5, HERIC, etc., do not have the bidirectional capability either. Therefore, scholars, scientists, engineers are continuously investigating bi-directional power conversion techniques for solar energy storage system. Novel topologies and control schemes are proposed to bridge the

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technology gap.

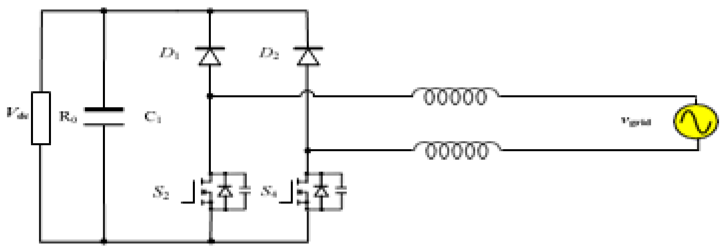
Based on half-bridge cell, a high efficiency dual buck-type inverter along with an admittance-compensated quasi-proportional resonant controller is proposed in [18] to ensure high power quality and precision power flow control. It is a half-bridge-type inverter, and it is more suitable for 110Vac grid considering 650V metal-oxide-semiconductor field-effect transistor (MOSFET) voltage stress. A cascade dual- boost/buck half-bridge converter based on the dual buck-type inverter is proposed for grid-tie transformer-less battery energy storage systems [19], no shoot-through issue is achieved with more units cascaded for high voltage applications. Furthermore, a dual buck-type full bridge bidirectional AC-DC converter is proposed in [20], utilizing two split ac-coupled inductors that operate separately for positive and negative half grid cycles in both inversion and rectification operations. It works as an ac-switch transformer- less inverter like HERIC circuitry in inversion mode and bridgeless power factor corrector (PFC) in rectification mode. The common mode (CM) voltages and associated leakage currents can be minimized in the proposed topology both in inversion and rectification modes. Based on the high- frequency leg (HFL) technique, Reference [21] further improves the dual buck-type full bridge bidirectional AC-DC converter with discontinuous current mode/continuous current mode operations.

For full-bridge type inverter, classic H5, HERIC, etc. transformer-less PV inverters do not have the bidirectional capability [21]. However, these topologies and derived circuitries such as numerous H6 inverters are the dominant circuits in single phase transformer-less PV applications. Since bidirectional power capability is a challenge to existing H6 inverters, the motivation of this manuscript is to find an advanced solution for them. In this paper, the relationship between bridgeless PFC boost rectifier and transformer-less inverter is reviewed and expounded at first. Then, a novel modulation method is proposed for single phase H6 inverter reform. It not only has bidirectional power flow feature but also retains the existing H6 inverter advantages, e.g. CM voltage and high efficiency. At last, PSIM Simulations and experimental test results verify the proposed single phase bidirectional H6 rectifier/inverter.

II. THE RELATIONSHIP BETWEEN BRIDGELESS PFC BOOST RECTIFIER AND TRANSFORMER-LESS INVERTER

In most cases the boost topology is used for single phase active power factor correction with input diode rectifier. The current have to pass at least 3 semiconductors including 2 diodes. Classic bridgeless PFC boost rectifier using split chokes without the input rectifier for each half-

+



(a) Basic bridgeless PFC boost rectifier

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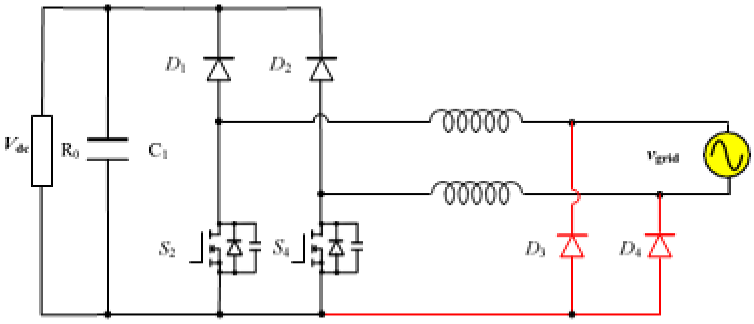
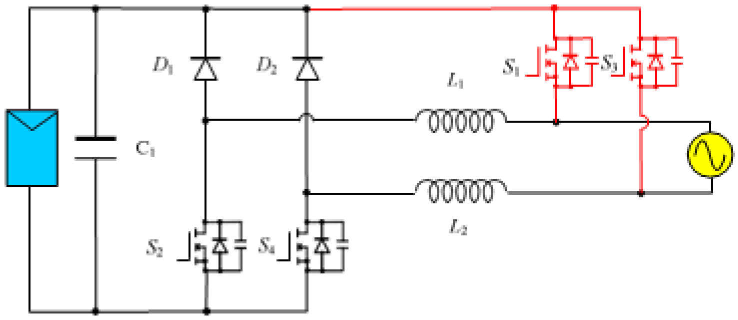
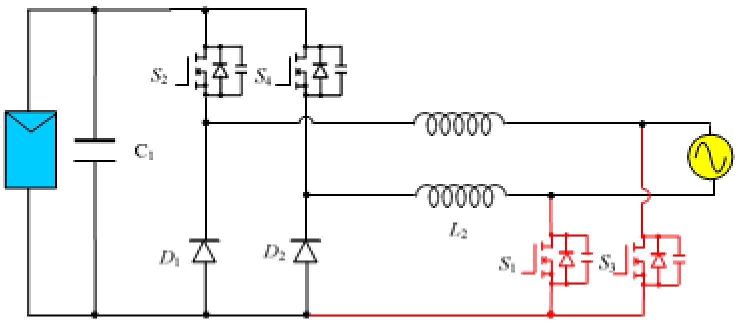


(a) Improved bridgeless PFC boost rectifier



(c) Transformer-less inverter with open emitter in the high side



(d) Improved transformer-less inverter with open emitter in the low side
Figure 1 The relationship between bridgeless PFC boost rectifier and Transformer-less inverter

wave in Fig.1 (a) is proposed. The problem is that the connection of both input lines to a PFC choke. The outcome of this is the floating of the output with high frequency relative to input source.

A new topology invented by Temesi Ernö and Michael Frisch in Vincotech does solve the problem [22]. Two chokes with the same inductance as in the standard boost topology are required. But only 1 inductor is used per half wave. The other one is bypassed by additional rectifiers as Fig. 1(b) illustrated. It is interesting to find that 4 years later Michael Frisch and Temesi Ernö also proposed transformer-less inverter with open emitter in the high side in Fig.1(c), which is

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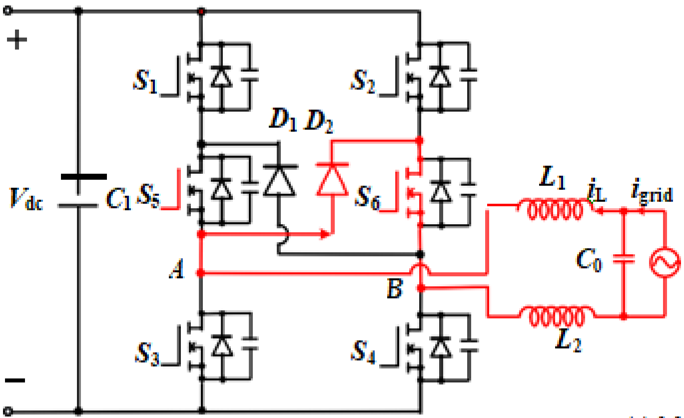
switched only with 50Hz as D_3, D_4 in Fig.1 (b) [23].

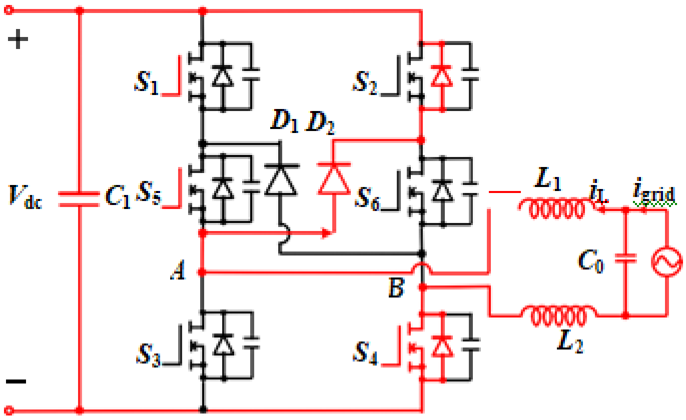
Similarly, another transformer-less inverter with open emitter in the low side is proposed in [24] as Fig.1 (d) illustrated. The basic idea behind it is to associate two parallel step-down converters with the output connected to the load using opposite polarities. It is derived from [25], where one of the discussed power-factor correction circuits was modified to get a reverse power flow.

In general, Fig.1 summarizes relationship between bridgeless PFC boost rectifier and transformer-less inverter, the essence of variant circuits is to find a reverse power flow approach, which would help bidirectional rectifier/inverter developed.

A. Bidirectional H6 Rectifier/Inverter Operation Modes



(a) Mode 1



(b) Mode 2

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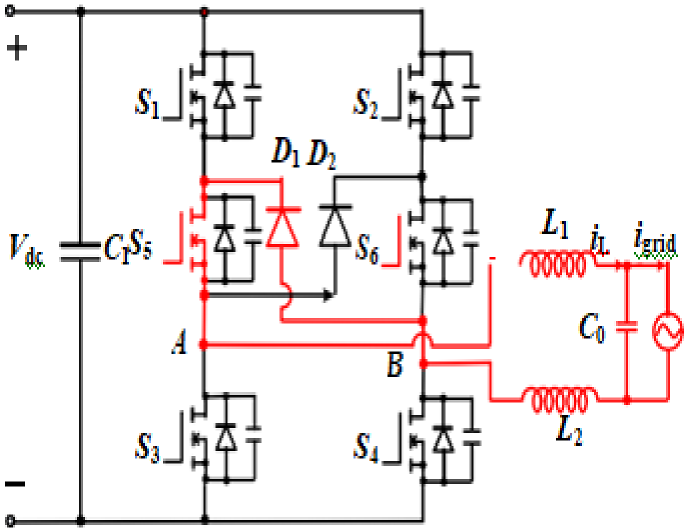
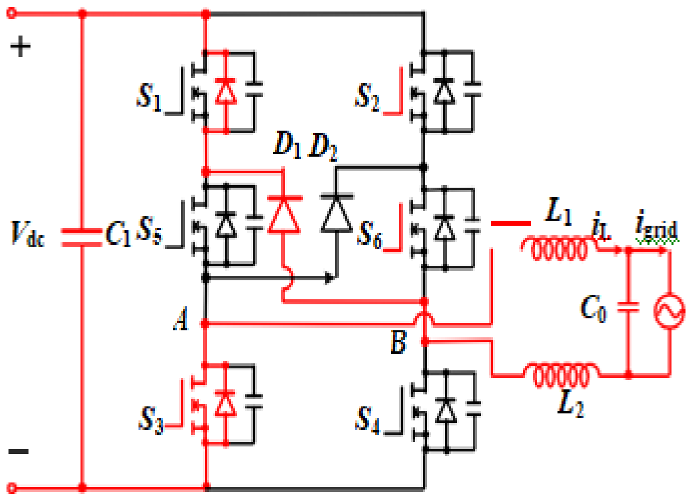


(c) Mode 3



(d) Mode 4

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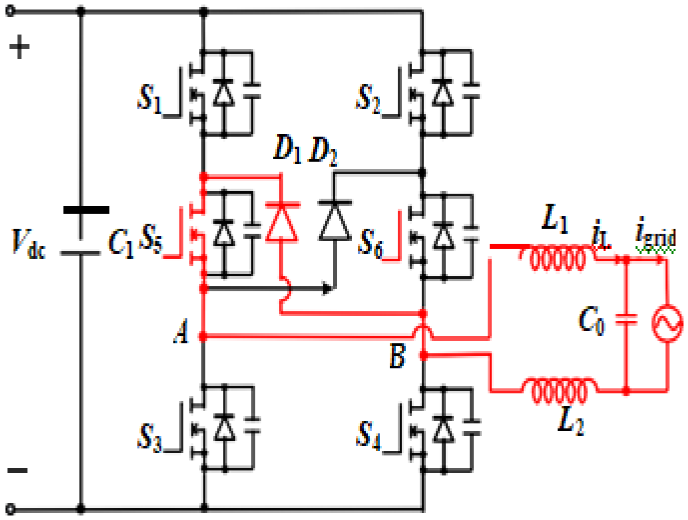

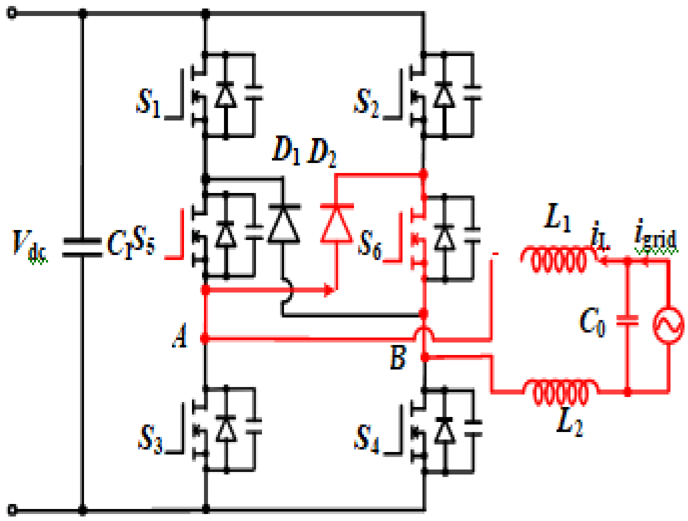

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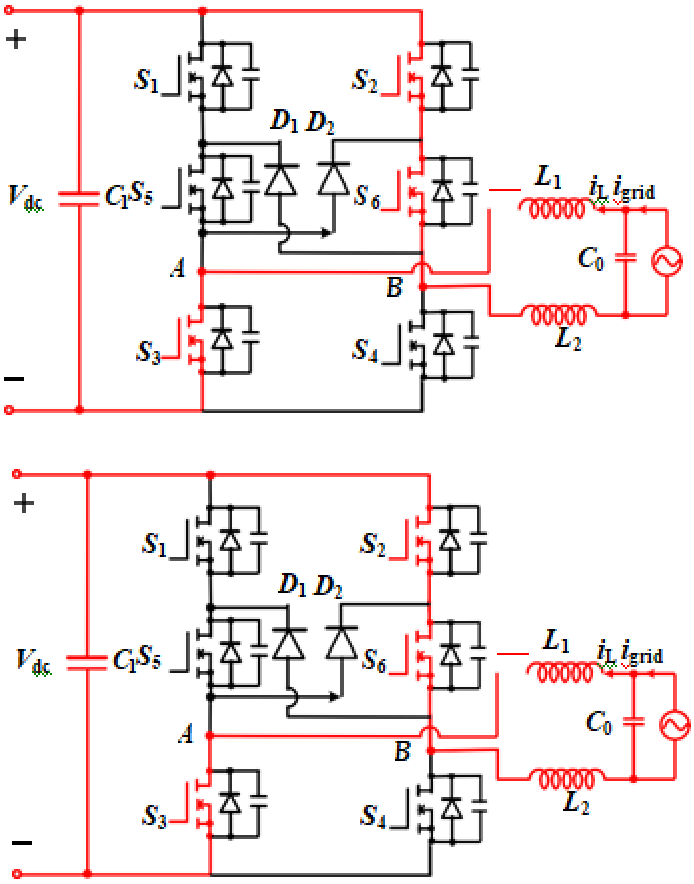

H6 inverter operation modes

III. DISCUSSION AND DESIGN CONSIDERATION

A. Advanced DM, CM features for bidirectional H6 converter with proposed modulation method

With detail operation modes analyzed in above section III, Tab.1 further summarizes some important features for the bidirectional H6 inverter. It is found that no matter it is a rectifier or inverter, common mode voltage of the bidirectional H6 inverter is almost a constant dc value, which would eliminate inverter's leakage current and improve EMC characteristic of PFC converter.

On the other hand, the differential voltage changes between V_{dc}, 0, and $-V_{dc}$. It is a typical three level voltage, which indicates good power quality of grid side, no matter it is a rectifier or inverter.

Modulation comparison for bidirectional power flow and unidirectional power flow

In Tab.1, it is found that H6 inverter operation modes with proposed modulation strategy or traditional modulation method are almost the same. The differences are high frequency switching patterns for with S_5 and S_6 with dashed line in Fig. 4(b). Actually, the dashed switching pulses could also be removed for inverter mode. For the same reason, line frequency switching pulses for with S_5 and S_6 with dashed

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TAB.I COMPARISON SUMMARY

Figures	Traditional Hybrid Modulation Method	Improved Hybrid Modulation Method	Corresponding Current paths	Level	
				v_{cm}	v_{dm}
Figure 5(a)	/	Rectifier Mode 1	grid, L_1, D_2, S_6, and L_2	0.5V$_{dc}$	0
Figure 5(b)	/	Rectifier Mode 2	grid, L_1, D_2, D_{S2}, dc side, S_4 (D_{S4}), and L_2	0.5V$_{dc}$	V$_{dc}$
Figure 5(c)	/	Rectifier Mode 3	grid, L_2, D_1, S_5, and L_1	0.5V$_{dc}$	0
Figure 5(d)	/	Rectifier Mode 4	grid, L_2, D_1, D_{S1}, dc side, S_3 (D_{S3}), and L_1	0.5V$_{dc}$	-V$_{dc}$
Figure 6(a)	Inverter Mode 1	Inverter Mode 1	S_1, S_5, L_1, grid, L_2, and S_4	0.5V$_{dc}$	V$_{dc}$
Figure 6(b)	Inverter Mode 2	Inverter Mode 2	grid, L_2, D_1, S_5, and L_1	0.5V$_{dc}$	0
Figure 6(c)	Inverter Mode 3	Inverter Mode 3	grid, L_1, S_3, dc side, S_2, S_6, and L_2	0.5V$_{dc}$	-V$_{dc}$
Figure 6(d)	Inverter Mode 4	Inverter Mode 4	grid, L_2, D_1, S_3, and L_1	0.5V$_{dc}$	0

line could also be removed for rectifier mode as Fig.4 (a). In this way, modulation strategies for both modes are different and should be changed with mode transfer. For control simplicity, we choose the same modulation method including some redundancy switching signals.

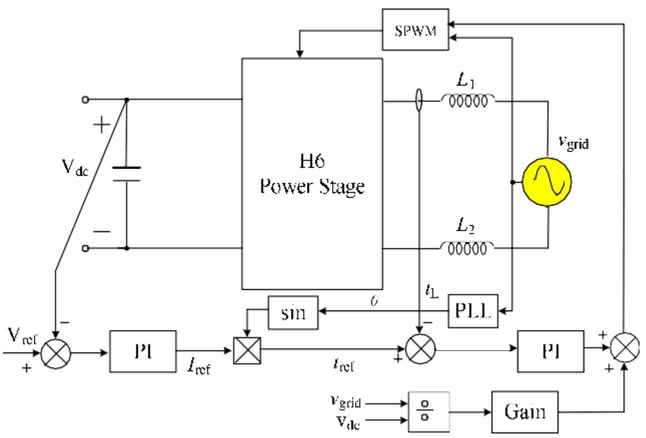
On the other hand, differences between Fig.4 (a) and Fig.4

(c) are that high frequency switching pulses adopted in S_5 and S_6 for rectifier mode, while line frequency switching pulses adopted in S_5 and S_6 for inverter mode. Corresponding current paths in Tab.1 further illustrate that body diodes are used in rectifier mode while they are not adopted in inverter mode. These two would affect the efficiency of the rectifier mode, which is the inevitable cost with only concise modulation

(d) improvement adopted. Fortunately, single H6 inverter solution is suitable for small power fields, where battery storage is adopted for emergency usage. The slightly efficiency decrease is acceptable for practice.

C. Bidirectional H6 rectifier/inverter control method

(e) Fig.7 shows the control block of the bidirectional H6 converter. The HV bus voltage V$_{dc}$ is regulated by the dc bus feedforward voltage loop control. The output current magnitude I_{ref} is given by the voltage loop.



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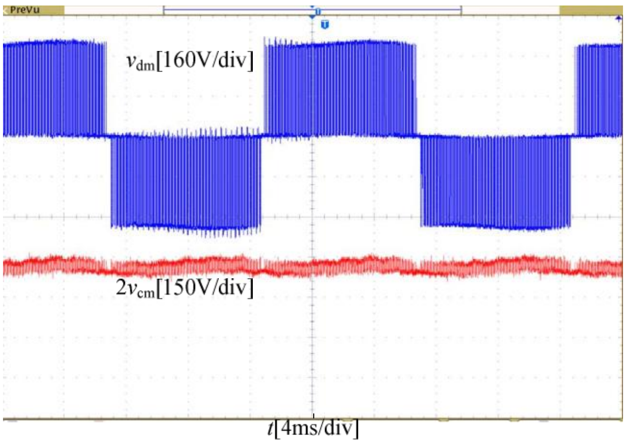
A. Experimental Test Results

The figure shows the 5kW bidirectional prototype photograph based on H6-typer topology. Detail test results are provided below.

Fig. 11(a) shows that the ac current is of the opposite phase from the ac current, while ac current and ac voltage in Fig.11(b) maintain the same frequency, as well as phase. The two curves are typical rectifier and inverter waveform with power factor =-1, and 1, respectively. Double line frequency dc link voltage ripple is also observed in Fig.11, it is a typical single phase system feature. The grid current total harmonic distortion (THD) of the rectifier mode and inverter mode is 3.28% and 2.64%, respectively, which both indicate high grid current performance.

The most known bidirectional converter is bi-polar modulation single phase full bridge H4 converter. It is proven that H6-type converter is more efficient than bi-polar modulation H4 inverter due to body diode is replaced with extra independent diode at the cost of more devices. Following this way, with more active and passive devices enrolled, dual buck-type converter, three level converters and their derived converters would get more high efficiency but the circuit structures would be more complex. Therefore, considering H6-type converters are the dominant circuits in single phase transformer-less PV applications, the proposed methodology would be regarded as a good trade-off for high cost performance concern.



IV. SIMPLE SWITCHED CAPACITOR FOR MINIMIZING ZERO-CROSSING DISTORTION

From analysis in above section, a simple switched capacitor circuit is series connected in the ac power supply link to improve input current performance shown in Fig.8. Two bidirectional switches (S2, S3) are used to control the switching capacitor to minimize zero-crossing distortion and maintain charge balancing for the capacitor in one input line frequency. Bidirectional switches can use two unidirectional switching devices in practical application. The corresponding operation principle and drive signals for S2 and S3 are shown in Fig.9. In the duration [0, □/2], S3B is turned on, the positive voltage (*VC+*) of the capacitor supplies the enough current slow rate so the current can ramp up to follow the reference.

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Meantime, the capacitor discharges from *VC+* and then recharges in reverse direction to *VC-* (|*VC+*| = |*VC-*|). In the duration [□/2, □], S2B is turned on, capacitor is bypassed and the input current in the primary loop is the same as traditional single-phase PFC. In the duration [□, 3/2□], S3A is turned on, the negative voltage (*VC-*) of the capacitor supplies enough current slow rate through diode D2, D4. Meantime, the capacitor discharges from *VC-* and then recharges in reverse direction to *VC+* (|*VC+*| = |*VC-*|). In the duration [3/2□, 2□], S2A is turned on, capacitor is bypassed and the input current in the primary loop is the same as traditional single-phase PFC. Therefore, the capacitor does not need backup power supply and the absolute value of *VC+* is equal to that of *VC-* in one input line frequency. There is one note here, switching actions
of S2 S3 occur at the zero crossing of the input current to
avoid the input current clamed to zero before the zero -crossing of the input voltage. So the simple switched capacitor circuit can reduce, even eliminate zero-crossing distortion with good current loop design in theory. Furthermore, the blocking voltage of one switching device in the switched capacitor compensator is half of the maximum capacitor (C) voltage in steady state. And the required charging voltage of the boost inductor at zero-crossing of input voltage is much smaller than
output voltage. Therefore, low voltage rating switching devices may be used. With low voltage rating switching devices operating in low switching frequency, the design cost and efficiency of single-phase PFC converters may not be seriously deteriorated. In one input line frequency, the slow rate of input
current achieves maximum at zero-crossing point, so the required minimum charging voltage across the capacitor can be calculated as follows:

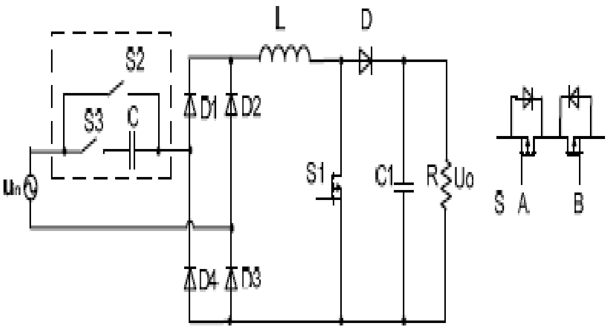
$$V_{rec} = L\frac{di}{dt}\bigg|_{i=I_m\cdot\sin(\omega t),\,\omega t=0} = \omega L I_m \qquad (1)$$

In the duration [0, π/2], the capacitor discharge from V_{C+} and then recharge in reverse direction to V_{C-} and the absolute value of V_{C+} should be equal to that of V_{C-}

$$V_{C-} = \frac{1}{C}\int_0^{\pi/2} I_m \sin(\omega t) + V_{C+} = \frac{I_m}{\omega C} + V_{C+} \qquad (2)$$

The required capacitance of the capacitor is:

$$C_{max} = \frac{1}{2\omega^2 L} = \frac{1}{8\pi^2 f_{line}^2 L} \qquad (3)$$



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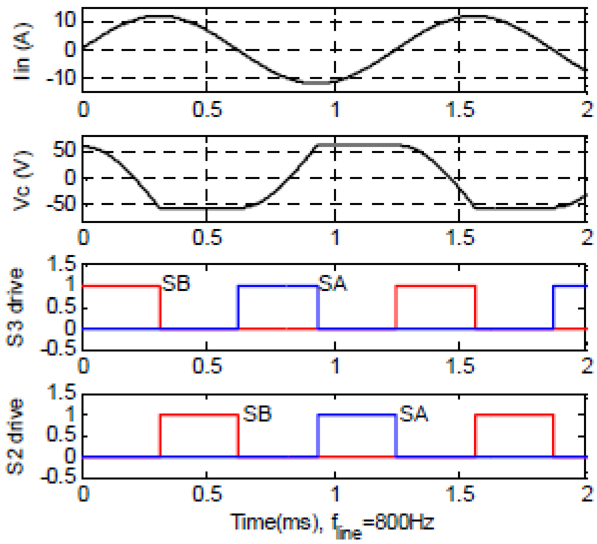

Fig.9. Control signals for S2 and S3.

V. CONCLUSION

With simple control the simple switched capacitor can avoid input current being clamped to zero before the zero crossing of the input voltage and supply enough input current and raising the slope after zero crossing of the input voltage. Aiming solar energy storage system, this paper improves a grid-tied single phase H6 PV inverter from unidirectional power flow to bidirectional power flow. A unified hybrid modulation method with minimized zero crossing distortion is achieved. The main advantages of the proposed solution can be summarized as:

1) Compared with the traditional hybrid modulation method for power rejection to grid only, a simple modification in the switching patterns is just needed for solar energy storage system with H6 type topology.

2) Battery storage is adopted for emergency usage in small solar energy storage system. Therefore, a slight cost of efficiency decreases in rectifier mode due to the partly used body diodes is acceptable, and the excellent DM/CM voltage features of the H6 circuitry in both rectifier and inverter modes are totally achieved.

The improved hybrid modulation method would be easily modified and applied to other H6 and similar topologies.

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