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Bidirectional H6 Rectifier/Inverter for Autonomous PV Applications

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ABSTRACT: Transformer-less Photovoltaic (PV) inverters are more commonly used due to high performance, low cost and light weight, etc. Nevertheless, in the potential, H5 and HERIC-based transformer-less PV inverters will not have a bi-directional capacity for the solar energy storage network. With the topology derivation history checked from rectifier to inverter, the nature of the bi- rectifier/inverter is unveiled. This proposed work, therefore, suggests an innovative bi-directional technique for the chosen H6 inverter topology with just a changed modulation approach, whereas the others stay the same. In rectifier and inverter modes, an outstanding three-level voltage function is accomplished for the H6 circuitry, whereas the leakage current problem is removed at the same time with an enhanced modulation process. Simulations and laboratory tests validate the experimental single-phase, bi-phase H6 rectifier/inverter technique.

KEYWORDS: Rectifier, Inverter, Photovoltaic.

I.INTRODUCTION

The extensive use of fossil fuels and nuclear energy has caused major pollution and safety problems, such as the nuclear power plant in Fukushima, Japan. Therefore, to reduce environmental damage, many countries have committed to developing green energy, such as solar and wind energy. In addition to improvements in the conversion efficiency of green energy, the storage and reuse of excess energy have become important research topics. Thus, high-step-up/step-down converters have become important research subjects. Converters with high conversion ratios [1] can be used in energy storage systems, high-intensity discharge lamps, high power applications, communication power, solar power, and uninterruptible power supplies.

Then, a novel modulation method is proposed for single-phase H6 inverter reform. It not only has a bidirectional power flow feature but also retains the existing H6 inverter [2] advantages, e.g. common mode voltage and high efficiency. At last, MATLAB simulations and experimental test results verify the proposed single-phase bidirectional H6 rectifier/inverter. Photovoltaic power generations are continuously booming in recent years, driven by an imperative demand for clean and reliable electricity.

With high penetration PV installation in the grid, PV inverter needs to play a more active role considering grid capability and stability issues. Besides well-known harmonic limits [3] and anti-islanding [4] requirements, new grid codes and standards are issued by many countries, committees, and utilities. Among them, leakage current limit, Low Voltage Ride-Through (LVRT) under grid faults, grid active/reactive power support issues have been released in succession for safety concern, grid voltage and frequency stability.

Numerous topologies and control schemes [5] are proposed to bridge the technology gap between codes and products by academia and industry. For leakage current issue, a leakage current over 300 mA must trigger a break within 0.3s. Traditional unipolar full-bridge four switches inverter is replaced by the novel H5, HERIC, H6 circuits for single-phase string grid-tie applications.

II. LITERATURE SURVEY RELATED TO POWER CONVERTERS

- Huang-Jen Chiu (2018) preferred a single-stage bi-directional converter is used. The converter switches are made to have soft-switching features. As a result, high power factor and efficiency is achieved. A laboratory protocol was developed and the outcomes are verified.
- Oscar Garcia (2019) presented a bi-directional topology in single-stage ac to dc converter. Fast output voltage regulation is achieved using a single switch and a single control loop. Though the line current is non-sinusoidal the standard IEC 1000-3-2 is satisfied with low-frequency harmonics for medium power (50-500W). The main

advantage is its simplicity, size and efficiency. The other advantage is that the voltage on the storage capacitor is clamped to the input voltage so no additional voltage stress.

- ChongmingQiao (2019) surveyed single-stage power factor corrected rectifiers. In most of the single-stage, power factor control rectifiers boost converter is connected with a forward or a bi-directional dc-dc converter. It is found that an energy stored capacitor is connected either in series or in parallel. The second part appears to be important and many topologies have been implemented by combining a 2- terminal or 3- terminal boost cell. As per the analysis, the single-stage PFC topologies appear to be electrically equivalent to one another.
- A new single-stage boost topology for electronic ballast in multiple fluorescent lamps is designed. In this, the boost converter is operated in discontinuous conduction mode and constant frequency which gives high power factor. Compared to conventional electronic ballast the proposed electronic ballast gives a significant reduction in cost. Ying-Chun Chuang (2017) designed the soft switching and circuit parameters with high accuracy to obtain high power factor. When more number of lamps is used the cost reduction is high. The theoretical and experimental results prove that the power factor is almost unity and Total Harmonic Distortion (THD) is low.

III. PROPOSED H6 RECTIFIER/INVERTER

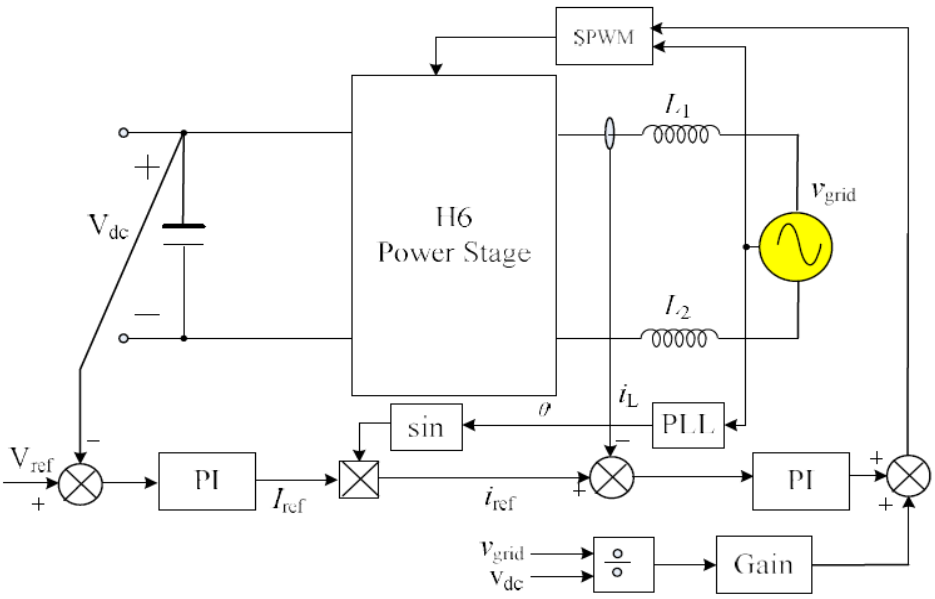


Fig. 1 Block diagram of the proposed H6 Rectifier/ Inverter

Fig.1 shows the control block of the H6 converter with bidirectional power flow current reference value $i_{ref}$is obtained by I_{ref}multiplied by a sine table which is synchronous with the grid voltage [6] through PLL circuit. A fast current inner loop guarantees the inductor current tracks the reference current value *i*, where grid voltage and dc bus voltage are used with a divider. Finally, the SPWM signals generation block.Fig.2 shows the circuit diagram of the proposed H6 Rectifier/ Inverter.

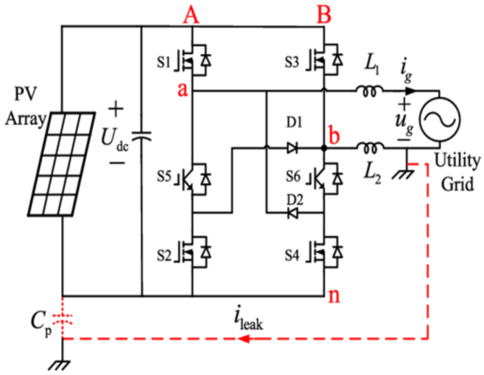


Fig.2 Circuit diagram of proposed H6 Rectifier/ Inverter

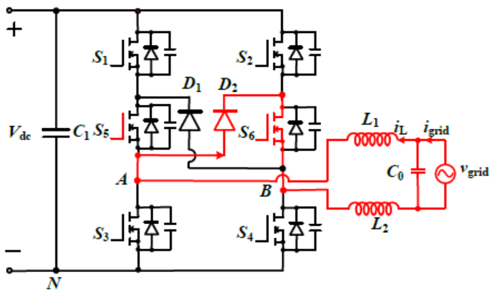
IV. MODES OF OPERATION

RECTIFIER OPERATION MODES

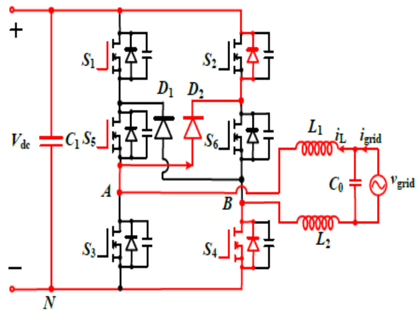
In H6 Rectifier Mode-1, during positive grid cycle, while $S_5$is always on, S_6 is turned on with high frequency, and grid charges the chokes L_1 and L_2 through a combination of the between grid, L_1, D_2, S_6, and L_2. Although S_5 is on, no current flow through it. However with the contribution of [7] shortening S_5, $V_{AN}= 0.5V_{dc}$ due to slit voltage between deactivated S_1 and S_3. For the same reason, $V_{BN}=0.5\ V_{dc}$ therefore,

Differential mode voltage $V_{dm} =V_{AB}= V_{AN} – V_{BN} =0$

Common mode voltage $V_{cm} = (V_{AN}+ V_{BN})/2= 0.5V_{dc}$.



Mode-1



Mode-2

In H6 Rectifier Mode-2, during positive grid cycle, while S_5 is always on, S_6 is turned off with high frequency. With active S_1 and S_4, continuous inductor current finds the demagnetizing path for chokes L_1 and L_2: grid, L_1, D_2, D_{S2}, dc side, S_4 (D_{S4}), and L_2, which is a reverse inner path for bidirectional [8] power flow. Since S_1 and $S_5$are turned on, bridge middle-point A is clamped to dc bus high side, then $V_{AN}=V_{dc}$. At the same time bridge, middle-point B clamped to dc bus low side, therefore, $V_{BN}=0$,

Differential mode voltage $V_{dm}=V_{AB}=V_{AN}-V_{BN}=V_{dc}$

Common mode voltage $V_{cm}=(V_{AN}+V_{BN})/2=0.5\ V_{dc}$

Mode-2

In H6 rectifier Mode-3, during negative grid cycle, while S_6 is always on, S_6 is turned on with high frequency, and it is a mirror state as mode-1 illustrated. The reverse power flow loop is a combination of the path between grid, L_2, D_1, S_5 and L_1. Similarly,

Differential mode voltage$V_{dm}=V_{AB}=V_{AN}-V_{BN}=0.5V_{dc}-0.5V_{dc}=0$

Differential mode voltage $V_{cm}=(V_{AN}+V_{BN})/2=(0.5V_{dc}+0.5V_{dc})/2=0.5V_{dc}$

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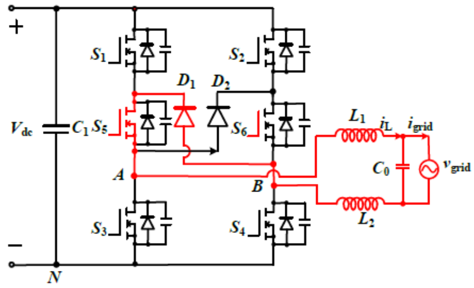
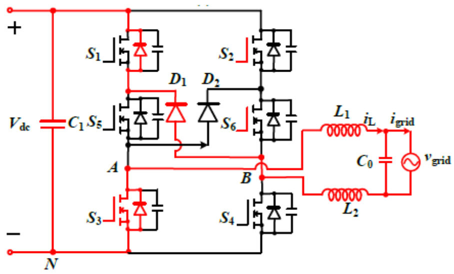


Mode-3



Mode-4

In H6 rectifier Mode-4, during negative grid cycle, while S_6 is always on,   is turned off with high frequency, and it is a mirror state as Mode-2 illustrated. Power flow loop is a combination of path between grid, L_2, D_1, D_{S1}, dc side, S_3 (D_{S3}), and L_2. Similarly,

Differential mode voltage $V_{dm}=V_{AB}=V_{AN}-V_{BN}=0-V_{dc}= -V_{dc}$

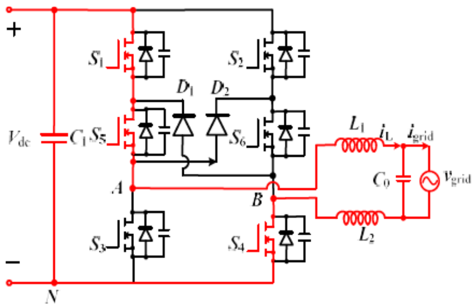
Common mode voltage $V_{cm}=(V_{AN}+V_{BN})/2=(0+V_{dc})/2=0.5V_{dc}$

INVERTER OPERATING MODES

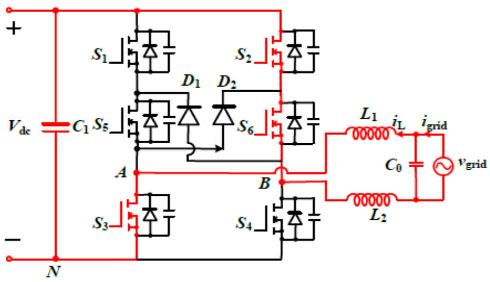
In H6 Inverter Mode-1, during positive grid cycle, while is S_5 always-on, $S_1$and S_4 are turned on synchronously with same high frequency [9], and dc side charges the chokes L_1, L_2, and grid through a combination of the path between S_1, S_5, L_1, grid, L_2, S_4.Since S_1 and S_5 are turned on, bridge middle-point A is clamped to dc bus high side, then $V_{AN} =V_{dc}$. At the same time, bridge middle-point B is clamped to dc bus low side, therefore, $V_{BN}=0$.

Differential mode voltage $V_{dm}=V_{AB}= V_{AN}-V_{BN}= V_{dc}$

Common mode voltage $V_{cm}=(V_{AN}+ V_{BN})/2=0.5 V_{dc}$



Mode-1



Mode-2

In H6 inverter Mode-2, during positive grid cycle while is S_5 always on. With deactivated S_1 and S_4, continuous inductor current finds the freewheeling path for chokes L_1 and L_2: grid, L_2, D_1, S_5 and L_2.

Although S_6 is turned on with high frequency at this time, no current flow through it. However, with the contribution of shortening S_6,$V_{BN}=0.5V_{dc}$ due to split voltage between deactivated S_2 and S_4. For the same reason, $V_{AN} =0.5V_{dc}$, therefore,

Differential mode voltage $V_{dm}=V_{AB}= V_{AN}-V_{BN}= 0$

Common mode voltage $V_{cm}=(V_{AN}+ V_{BN})/2=0.5 V_{dc}$

In H6 inverter Mode-3, during negative grid cycle while S_6 is always on, S_2, S_3 are turned on with the high frequency, and it is a mirror state as Mode-1 illustrated. The power flow loop is a combination of the path between grid, L_1, S_3, dc side, S_2, S_6, and L_2. Similarly,

Differential mode voltage $V_{dm}=V_{AB}=V_{AN}-V_{BN}= 0-V_{dc} = -V_{dc}$

Common mode voltage $V_{cm}= (V_{AN} +V_{BN})/2=(0 +V_{dc})/2=0.5V_{dc}$

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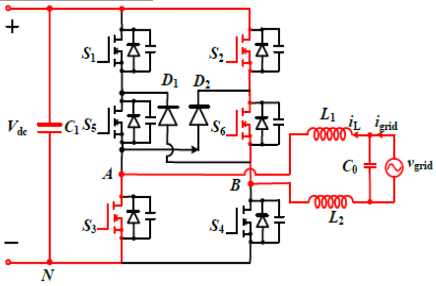
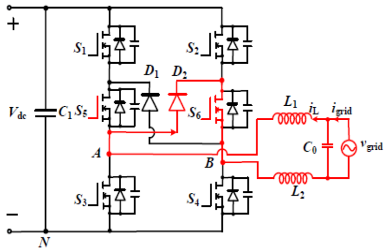


Mode-3



Mode-4

In H6 inverter Mode-4, during negative grid cycle, while S_6 is always on, S_5 is turned on with high frequency, and it is a mirror state as Mode-2 illustrated. Current Freewheeling loop is a combination of the path between grid, L_2, D_1, S_3, and L_1. Similarly,

Differential mode voltage $V_{dm}=V_{AB}= V_{AN} - V_{BN}= 0.5V_{dc} - 0.5V_{dc} =0$

Common mode voltage $V_{cm}=(V_{AN} + V_{BN})/2= (0.5V_{dc} + 0.5V_{dc})/2=0.5V_{dc}$

V. SIMULINK MODEL OF PROPOSED SYSTEM

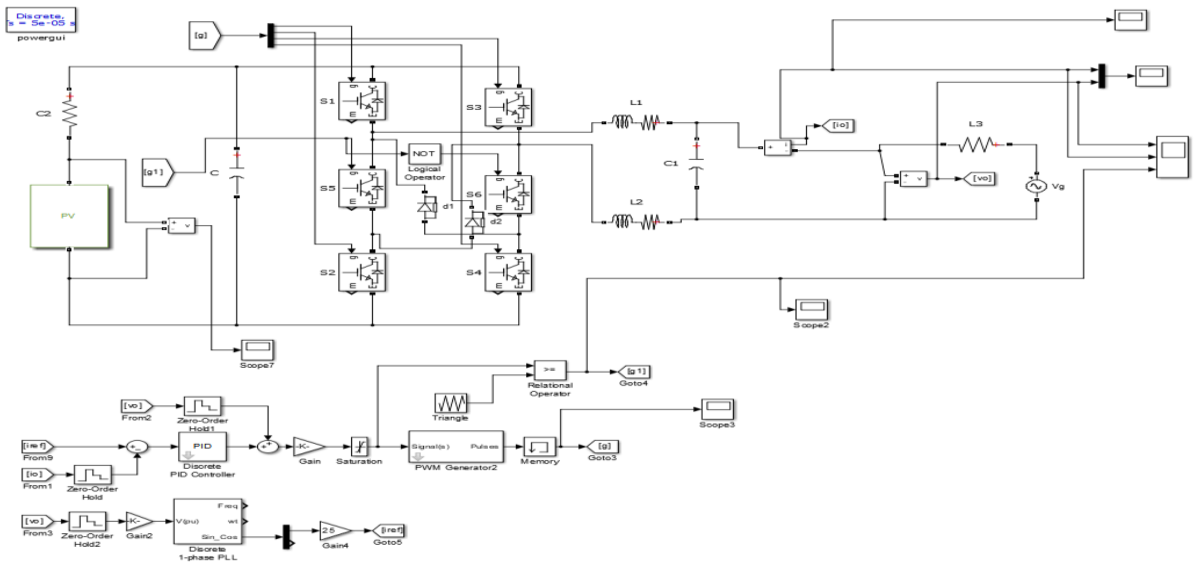


Fig.3 Simulink model

To verify the proposed hybrid modulation method for the H6 bidirectional converter, MATLAB Simulink [10] based simulations shown in Fig.3 and experimental test results are provided for verification, respectively.

SIMULATION RESULTS

In detail simulation results for H6 rectifier mode and inverter mode verification, including ac grid voltage, ac current, DM voltage, CM voltage and drive signals, which are predicted in this section.

Further provides current stress and voltage stress of the main device in the H6 rectifier. Due to the symmetrical structure [11] of the circuit, D_1, S_1, S_3, S_5 are chosen for device selection. It is found that the transient maximum current of them is given by the inductor current with high-frequency ripple considered. While the transient maximum voltage of them is clamped to the dc-link voltage. Considering the thermal issue and voltage spike, 1.5x-2x current/voltage derating coefficient would be acceptable.

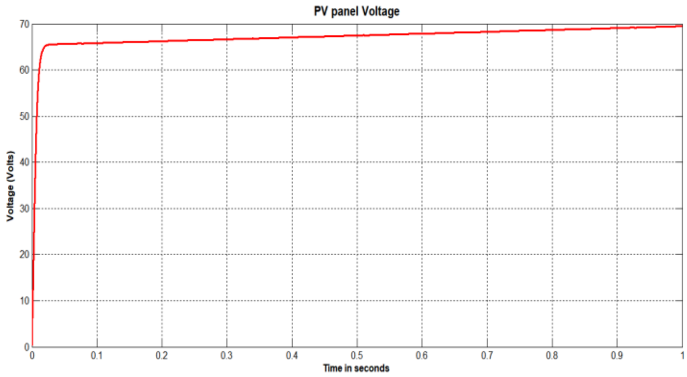


Fig.4 PV panel DC voltage

Fig.4 shows the PV panel DC output voltage attained the maximum within 1 second.

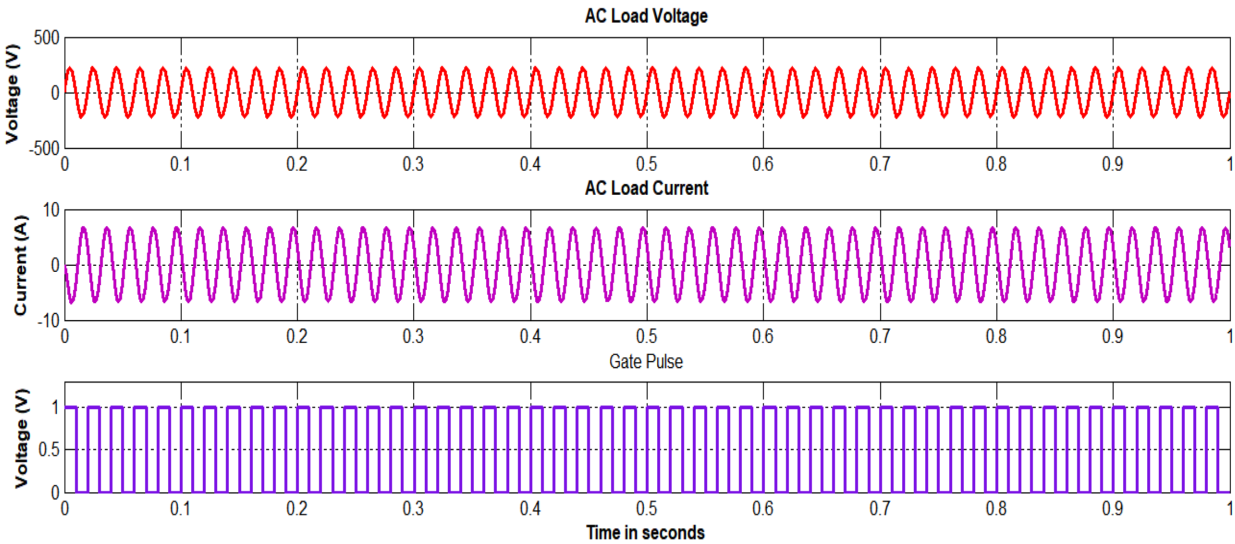


Fig.5 Inverter output voltage, current and gate pulse waveform

Fig..5 shows the AC load voltage, AC load current and PWM gate pulse.

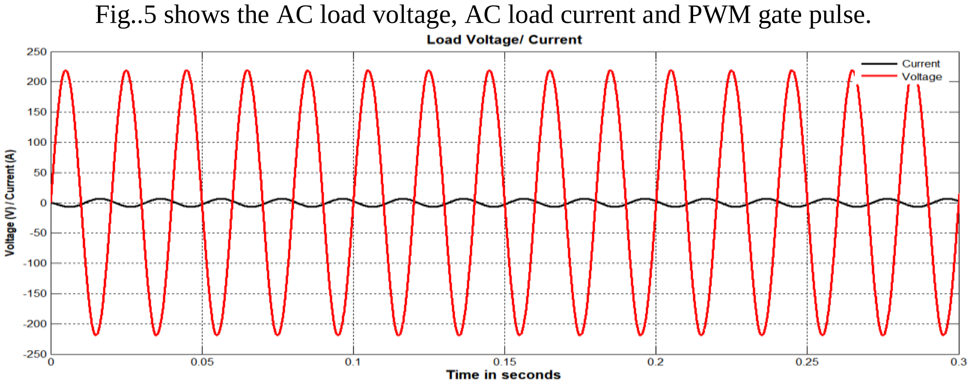


Fig.6 Voltage/Current waveform

Fig.6 shows the Load voltage and load current in a combined manner, the legends show the difference of magnitude.

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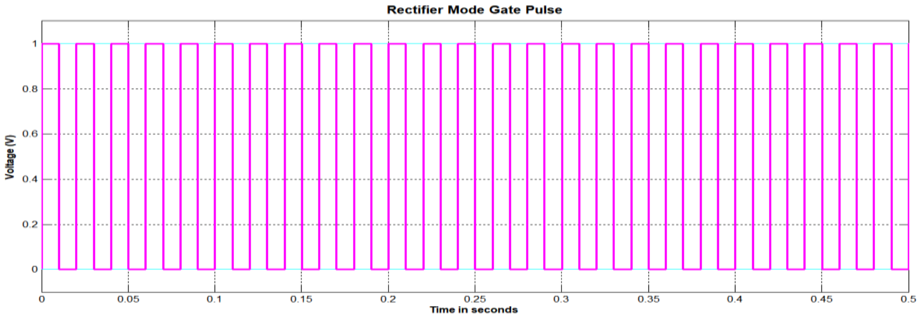

Fig.7 DC-DC converter gate pulse

TOTAL HARMONIC DISTORTION:

Further Fig.10 shows the 0.5kW bidirectional prototype photograph based on H6-typer topology. Detail test results are provided below shows that the ac current is of the opposite phase from the ac current, while ac current and ac voltage in maintaining the same frequency, as well as phase. The grid current Total Harmonic Distortion (THD)of the rectifier mode and inverter mode is 3.28% & 2.64%, shown in Fig.8 respectively, which both indicate high grid current performance.

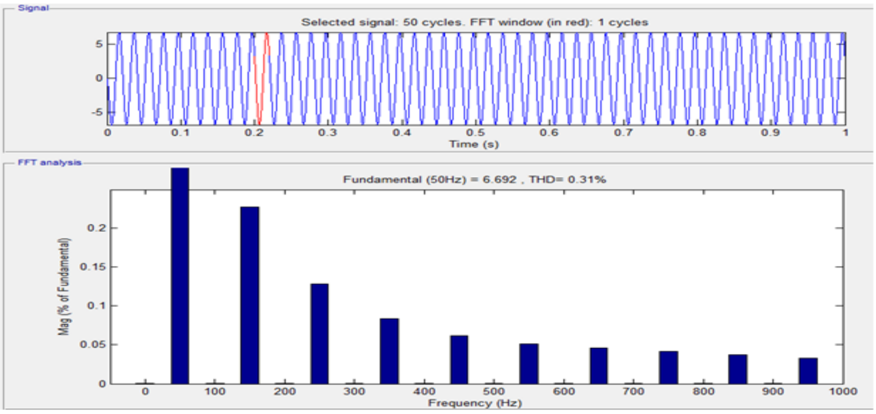

Fig.8 Total Harmonic Distortion

EFFICIENCY CURVE:

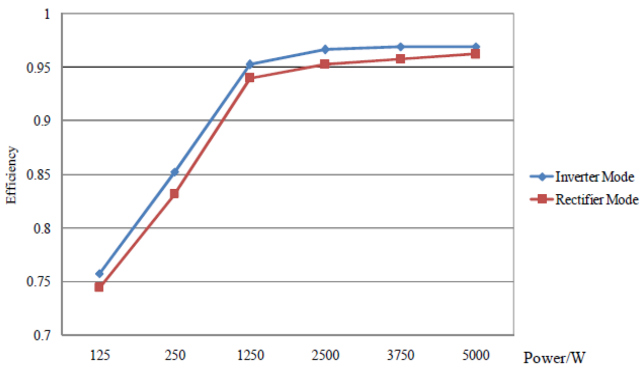

Fig.9 Efficiency curve

Last but not least, the efficiency curve of both the rectifier mode and inverter mode is shown in Fig.9. It is found that the maximum efficiency of the converter in inversion mode is 96.95%, while that in rectifier mode is 96.24% in rectification mode. In rectifier mode, switching two switches with high frequency and using body diodes for power flow paths will increase the switching losses of the converter, compared to the H6 inverter mode. It is the cost for bidirectional power capabilities like that in bi-polar modulation method and uni-polar modulation method for the full-bridge inverter. The efficiency of the H6 rectifier slights lower than H6 inverter. 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.

VI. HARDWARE KIT RESULTS

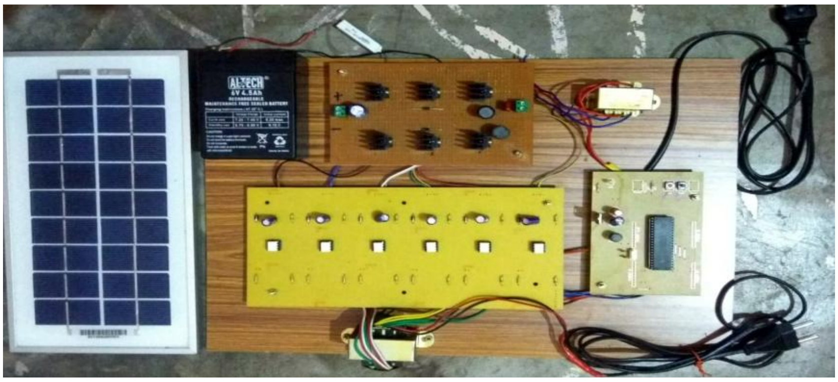

Fig.10 Hardware prototype model

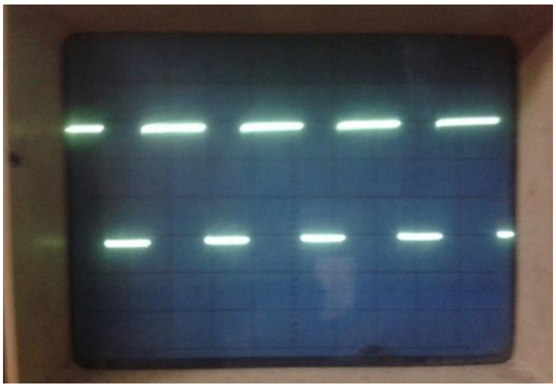

Fig.11 PWM based Gate pulse

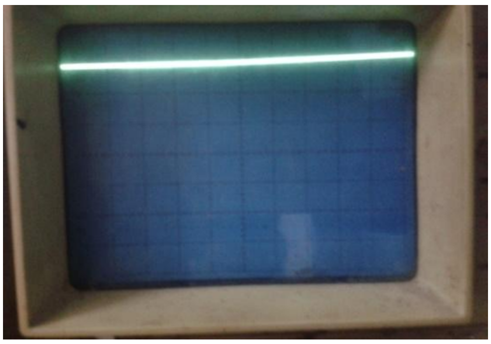

Fig.12 PV DC output voltage

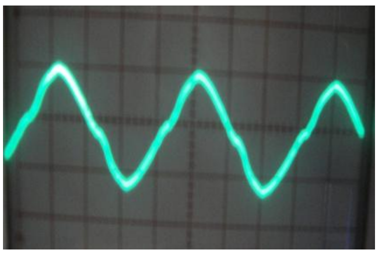

Fig.13 AC output voltage

Fig.11, Fig.12 and Fig.13 gives the PWM gate pulse generation, PV DC output voltage and AC output voltage across the load respectively.

VII. CONCLUSION

Compared with the traditional hybrid modulation simple method for power rejection to the grid only, a modification in the switching patterns is just needed for a solar energy storage system with H6 type topology. Battery storage is adopted for emergency usage in the 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 voltage features of the H6 circuitry in both rectifier and inverter modes are achieved. The improved hybrid modulation method would be easily modified and applied to other H6 and similar topologies.

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