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Analysis of Leakage Current Elimination in Single Phase Transformerless Inverter for Grid-Tied Photovoltaic Applications

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Abstract:

In photovoltaic (PV) application, it is possible to remove the transformer from the PV system in order to reduce size, losses, and cost and improve the efficiency. Due to the characteristics of low cost and high efficiency, the transformerless PV grid-connected inverters have been popularized in the application of solar electric generation system in residential market. Unfortunately, presence of the parasitic capacitor between the panel's metal frame and cells causes the leakage current issue. The leakage current increases current harmonics injected into the utility grid, the radiated, conducted EMI, and losses. Eliminating the leakage current is one of the most important issues for transformerless single-phase photovoltaic (PV) systems. This paper focuses on analysis of leakage current elimination in single-phase transformerless inverter for PV applications. A simple unipolar Sinusoidal Pulse-Width Modulation (SPWM) technique is used to modulate the inverter to minimize the switching loss, output current ripple, and the filter requirements.The main benefits of the proposed inverter are (1) The neutral of the grid is directly connected to the negative terminal of the PV panel, so the leakage current is eliminated, (2) low cost, (3) its compact size, (4) flexible grounding configuration, (5) capability of reactive power flow, and (6) high efficiency. A complete description of the operating principle and analysis of the proposed inverter are presented and simulation results are verified.

***Keywords*— Charge Pump Circuit, Grid Connected Inverter, Leakage Current Elimination, Photovoltaic, Transformerless Inverter, common mode voltage, parasitic capacitor, sinusoidal pulse width modulation, SPWM.**

I. INTRODUCTION

The photovoltaic (PV) systems operate in distributed generation applications in two different configurations: standalone and grid-connected [1]-[2]. In both applications usually some common components are used including PV panels, inverters and energy storage devices [3]. The energy storage devices mostly are used in the form of solid-state orland redox flow batteries along with hybrid fuel cell power generation systems [4]-[9]. The inverters are fundamental components enabling the integration of PV panels and energy storage systems to these hybrid energy systems. The PV power system has become more popular among renewable energy sources because it generates electricity with no moving parts, it operates quietly with no emissions and requires little maintenance [10]-[13]. Distributed grid connected PVs are playing an increasingly significant role as an electric supply resource and as an integral part of the electrical grid.

In PV applications a transformer is often used to provide galvanic isolation and voltage ratio transformations. However, these conventional iron and copper-based transformers increase the weight/size and cost of the inverter whilst reducing the efficiency and power density. Usually, the cost and size are two limiting factors for fully integrating the inverters within the grid. One possible solution to reduce the inverter's size and cost is to utilize the transformerless grid-connected inverters. Thus eliminating transformers is a great benefit to further improve the overall system efficiency and reduce the size and weight [14]-[17].However, the elimination of the transformer from the inverter's structure, introduces the possibility of the ground leakage current on the stray capacitor between the PV panels and the ground [18]. The leakage current reduces the efficiency of the inverter, increases the grid current distortion, and more importantly, decreases the safety of the overall system [19]. Therefore, the leakage current must be limited within a reasonable margin.

The paper is organized as follows. Single Phase Grid tied transformerless PV inverter topology is explained in section II. The charge pump circuit concept is explained in section III. Ground Leakage Current Elimination explained in section IV. A proposed inverter is derived in this section V, and the modulation strategy and operation principles are described in details. Matlab Simulation results of the proposed grid tied inverter are presented in Section VI. Experimental verification presented in Section VIIand finally conclusions are found in Section VIII.

II. SINGLE PHASE GRID TIED TRANSFORMERLESS PV INVERTER TOPOLOGIES

Various research works have been proposed recently to eliminate the leakage current using different techniques in a transformerless inverter [20]-[26]. For transformerless grid connected inverters, Full Bridge (FB) inverter, Neutral Point Clamped (NPC), Active NPC (ANPC)inverter [24] and many other topologies such as H5, H6 and HERIC were proposed to reduce the leakage current with disconnecting of the grid from the PV during the freewheeling modes [25]. However, these topologies are not totally free from Common Mode (CM) current or leakage current. The leakage current still exists due to the parasitic capacitor of the switch and stray capacitance between the PV panel and ground. So, some of these topologies require two or more filter inductors to reduce the leakage current, which leads to a rise in the volume and cost of the system [26].

However, they require a large number of active and passive components (more than 6 switching devices except H5), which increases complexity, cost, and size of the inverter. In addition, the higher number of switches in the current path during the active state increases the total on-state resistance R_{DS}, *on*, and hence, increases the conduction loss in the system, e.g., in H5, H6, where ≥3 devices are in series during the active state. The multilevel neutral-point-clamped (NPC) inverter is also suitable for reducing the leakage current; however, the input voltage or dc-link voltage must be more than twice that of the H-bridge type inverters (H5, HERIC, etc.).

Fig. 1 illustrates a single-phase grid tied transformerless inverter with CM current path, where *P* and *N* are the positive and negative terminals of the PV, respectively.

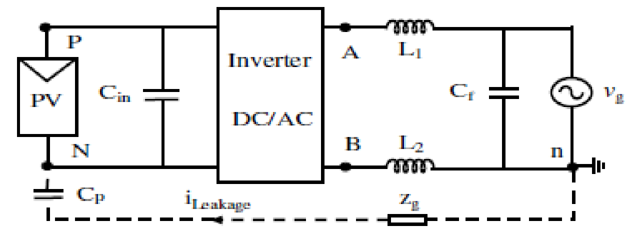

Fig.1. Block diagram of single-phase grid connected transformerless inverter with a leakage current path.

The leakage current ($i_{Leakage}$) flows through parasitic capacitor (C_P) between the filters ($L_1$and L_2), the inverter, grid and ground impedance (z_g). This leakage current may cause safety problems, reduce the quality of injection current to the grid, as well as decrease the system efficiency. In order to eliminate the leakage current, the Common Mode Voltage (CMV) (v_{cm}) must be kept constant during all operation modes.

The v_{cm} with two filter inductors (L_1, L_2) is calculated as:

$$V_{cm} = \frac{V_{An}+V_{Bn}}{2} + \frac{(V_{An}-V_{Bn})(L_2-L_1)}{2(L_2+L_1)} \quad (1)$$

where, v_{An} and v_{Bn} are the voltage differences between the midpoints *A* and *B* of the inverter to the dc bus minus terminal *N*, respectively. If $L_1 \neq L_2$ (asymmetrical inductor), v_{cm} is calculated according to (1) and the leakage current appears due to a varying CMV. If $L_1 = L_2$ (symmetrical inductor), v_{cm} is simplified to:

$$V_{cm} = \frac{V_{An}+V_{Bn}}{2} = Const. \quad (2)$$

In this state, the common mode voltage is constant and the leakage current is eliminated. The various Single phase grid tied transformerless PV inverter topologies:

A. H5 Inverter.
B. HERIC Inverter.
C. Virtual DC Bus Inverter.
D. Common mode Inverter.

A. H5 Inverter

The H5 inverter that is a FB based inverter topology, compared to the conventional FB inverter, needs one additional switch (*S_5*) on the dc side to decouple the dc side from the grid as shown in below Fig. 2.

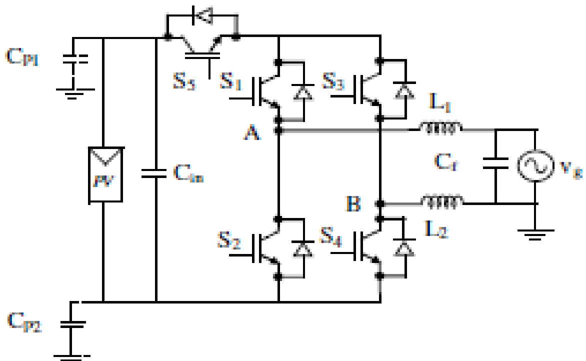

Fig.2. H5 Inverter.

This inverter has a variable CM voltage with a small leakage current and it suffers from low efficiency due to three switches operating at the same time.

B. HERIC Inverter

The Highly Efficient and Reliable Inverter Concept (HERIC) topology is shown in below Fig. 3.

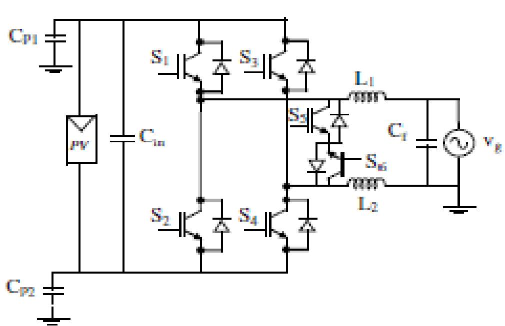

Fig.3. HERIC Inverter.

It needs two extra switches on the ac side to decouple the ac side from the PV module in the zero stage. HERIC combines the merits of unipolar and bipolar modulation. The main advantage of the HERIC inverter is its high efficiency due to only two switches operates at the same time in all operation modes. The main drawbacks of the HERIC topology are its the low frequency harmonics and reactive power flow is not allowed.

C. Virtual DC Bus Inverter

The Virtual dc bus Inverter topology is shown in below Fig.4.

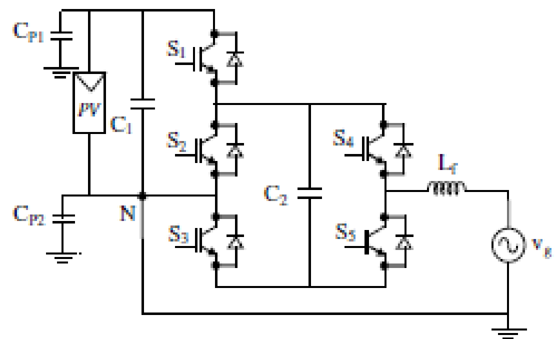

Fig.4. Virtual DC Bus Inverter.

The virtual dc bus inverter is composed of five IGBTs, two capacitors and one filter inductor L_f. Only one filter inductor is used in this topology to eliminate the leakage current, but it is very large. The virtual dc bus generates the negative output voltage. The main drawback of this topology is that there is no path to charge the capacitor C_2 during the negative cycle and this will cause a high output THD.

D. Common Mode Inverter

The Common mode Inverter topology is shown in below Fig. 5.

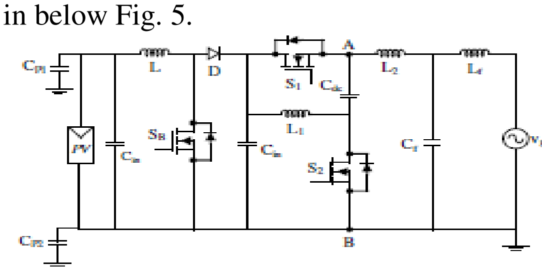

Fig.5. Common Mode Inverter.

The number of semiconductors used in this topology is low. However, the output voltage of this inverter is only two levels including positive and negative voltage without creating the zero voltage, which requires a large output inductor L_2 and a filter.

III. CHARGE PUMP CIRCUIT

The basic concept of charge pump circuit is shown in below Fig. (6)

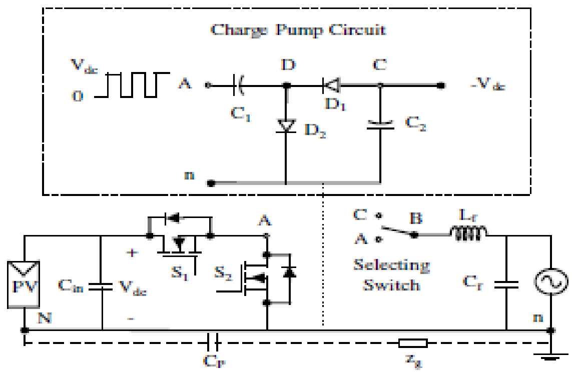

Fig.6. Charge Pump Circuit.

The circuit consists of two diodes (D_1, D_2) and two capacitors (C_1, C_2). This simple charge pump circuit gives a negative dc output voltage at the point of C equal to the voltage of point A. The capacitor C_1 is used to couple the voltage point of A to the node D. Two schottky diodes D_1 and D_2 are used to pump the output voltage. When the diode D_2 is forward biased, the capacitor C_1 is charged by diode D_2. The diode D_1 is reversed in this state. When the diode D_1 conducts, capacitor C_2 is charged through the capacitor $C_1$by using node n and switchS_2.

The charge pump circuit in the transformerless inverter has the following characteristics for grid tied applications.

- This circuit has a common line with the negative terminal of the input dc voltage and the neutral point of the grid that causes the leakage current to be eliminated.
- The charge pump circuit has no active device and it has a lower cost for grid tied applications.
- The capacitor of the proposed inverter charges every switching cycle, which reduces the size of the required capacitor with the switching frequency.
- The capacitor of the charge pump circuit charges with a switching cycle that eliminates the pulse duration sensitivity to generate the negative voltage.

IV. GROUND LEAKAGE CURRENT ELIMINATION

The stray capacitor between the PV panel and the ground is not negligible, and accordingly, there is a ground leakage current in the transformerless grid-connected inverters. This leakage current must be eliminated or reduced to a standard margin. In Fig. 7, the ground leakage current path in the proposed inverter is shown.

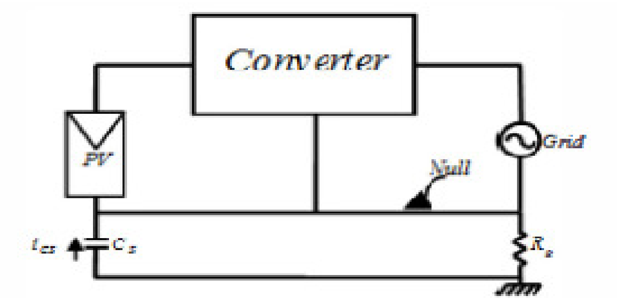

Fig.7. Ground Leakage Current Path.

According to Fig. 7, in the proposed inverter PV panel has common ground with the grid. As a result, the stray capacitor is bypassed and capacitor's voltage is constant, the ground current approaches zero.

$$i_{cs} = C_s \frac{dv_{cs}}{dt} \qquad (3)$$

V. PROPOSED TOPOLOGY

The proposed topology uses the charge pump circuit is shown below Fig. (8).

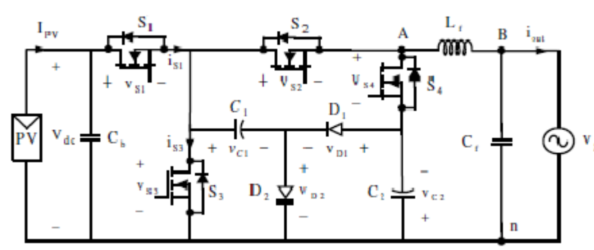

Fig.8. Proposed Topology.

It consists of four power switches (S_1-S_4), two diodes (D_1-D_2) and two capacitors (C_1-C_2) charge pump circuit. This new topology is modulated using simple SPWM. The waveform of the gate drive signals for the unipolar SPWM of the proposed inverter is generated according to the value of the modulation wave v_{ref} and the carrier wave v_c as shown in Fig 9.

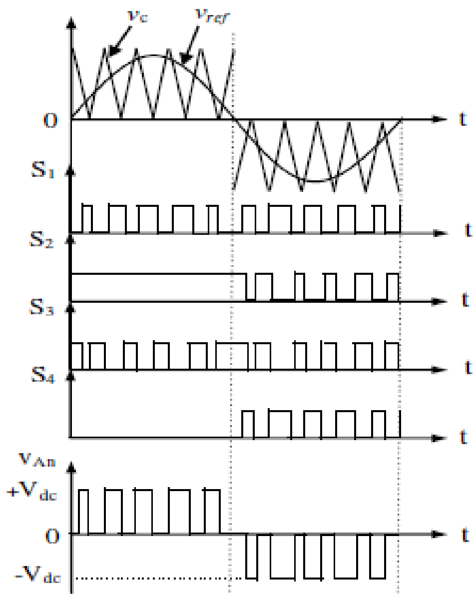

Fig.9. Unipolar SPWM gate pulses.

The output voltage (v_{An}) varies between $+V_{dc}$ and zero at positive cycle and varies between $-V_{dc}$ and zero at negative cycle according to the SPWM method.

Modes of operation:

It works based on 3 modes of operation given below:

1. Mode1 (Positive State)
2. Mode2 (Zero State)
3. Mode3 (Negative State)

Mode1:

During the positive half period of the grid, the switches S_1 and S_3 will be on and off with the switching frequency f_s to produce positive and zero voltage whilst, S_2 remains on for the whole positive half cycle. When the switches S_1 and S_2 are on, the output voltage of the inverter will be $+V_{dc}$. During this time interval, diode D_1 is reverse biased and D_2 is on, so the capacitor C_1 is charged through diode D_2 and the voltage across the capacitor C_2 maintains to be constant. This is called Positive state as shown in Fig.10.

Mode2:

During this period, when the switches S_2 and S_3 are on, the output voltage of the inverter will be 0. In this state, the capacitor C_1 and C_2 are connected in parallel through D_1.

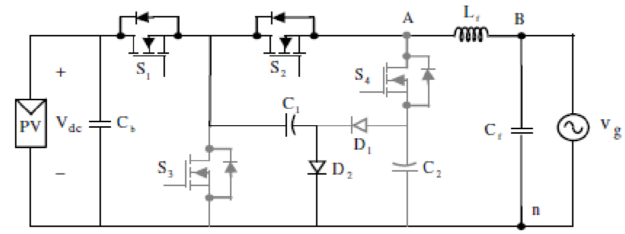

Fig.10. Positive State.

The Capacitor C_2 is charged by the capacitor C_1 with negative polarities up to $-V_{dc}$ by the charge pump circuit to provide the negative voltage level for the AC grid. This is called Zero state shown in Fig. 11

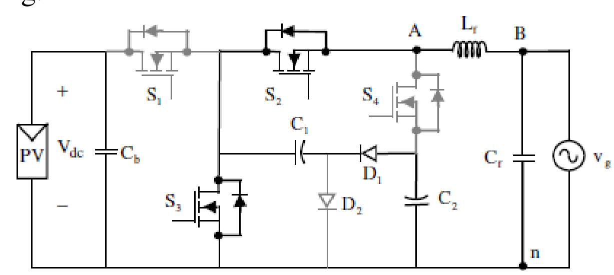

Fig.11. Zero State.

Mode3:

During the negative half period of the grid, the negative and zero voltage levels are produced by conducting S_4 and S_1.The negative voltage is generated when switch S_4 is turned on and the voltage across the capacitor C_2 appears at the inverter output voltage $-V_{dc}$. This is called Negative State shown in Fig. 12

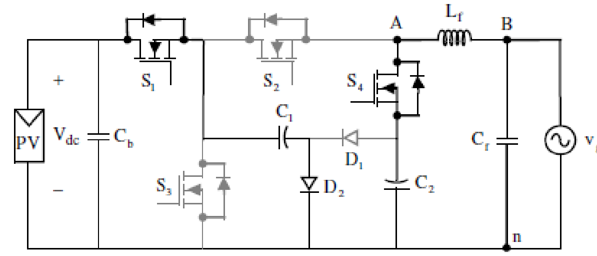

Fig.12. Negative State.

The following are the conduction of switching devices during 3 states

States	S_1	S_2	S_3	S_4
Positive	ON	ON	OFF	OFF
Zero	OFF	ON	ON	OFF
Negative	ON	OFF	OFF	ON

VI. SIMULATION RESULTS AND DISCUSSION

The Transformerless inverter with PV array is simulated using MATLAB and the results are presented. Fig 13 represents proposed circuit and the results

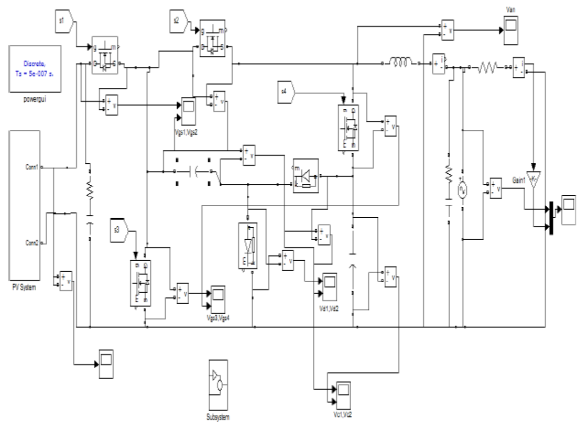

Fig.13. Transformerless Inverter with PV array.

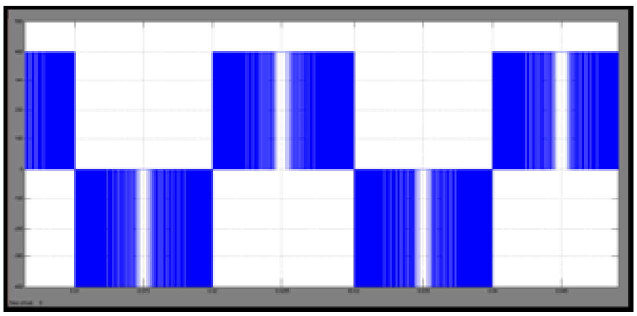

Fig.14. Three level output voltage across Van.

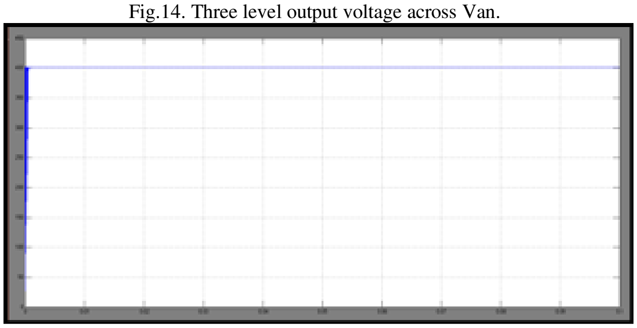

Fig.15. Voltage across PV cell.

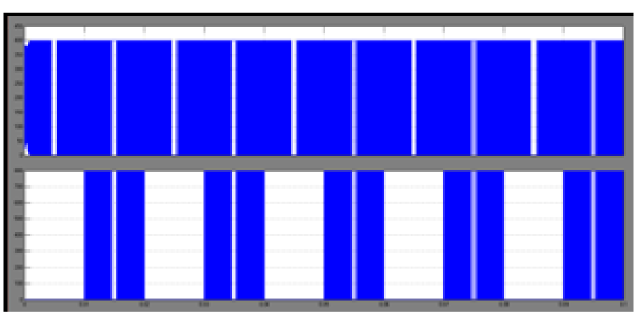

Fig.16. Voltage across V_{gs1}&V_{gs2}.

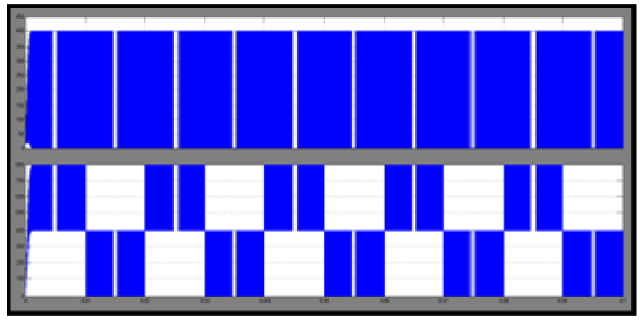

Fig.17. Voltage across V_{gs3}&V_{gs4}.

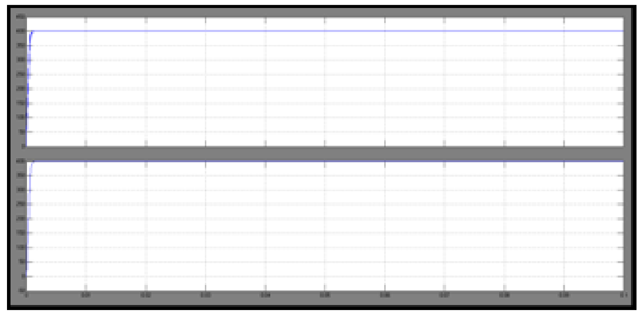

Fig 18 Voltage across capacitor

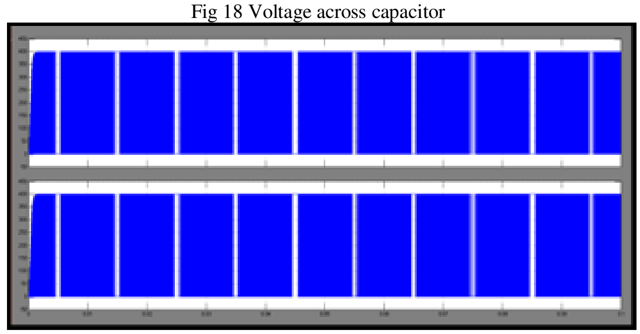

Fig 19 Voltage across diode

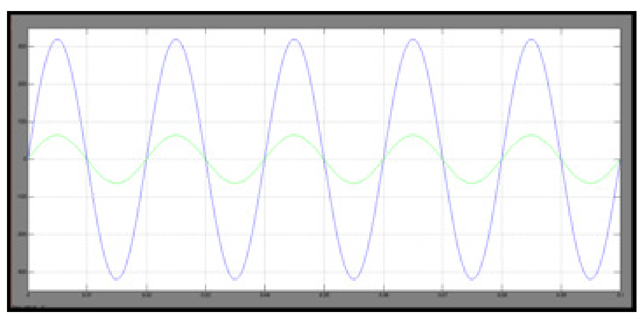

Fig 20 Output voltage at unity pf.

VII. EXPERIMENTAL VERIFICATION

The proposed topology of 500W single phase transformerless grid tied inverter has tested experimentally in laboratory. The Experimental setup of the single phase grid tied proposed inverter is shown in Fig. 21.

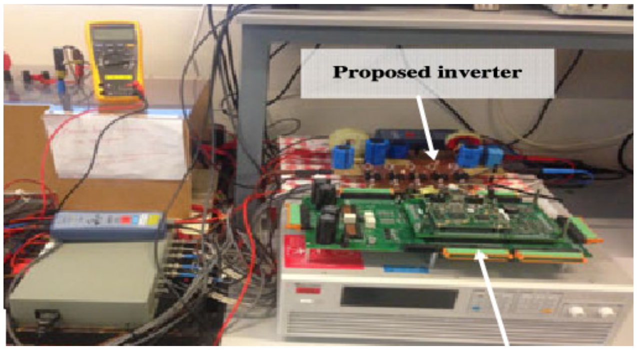

Fig. 21. Experimental setup of the single phase grid tied inverter

The experimental results of the proposed grid connected inverter with UPF (PF = 1) operation is shown in Fig. 22.

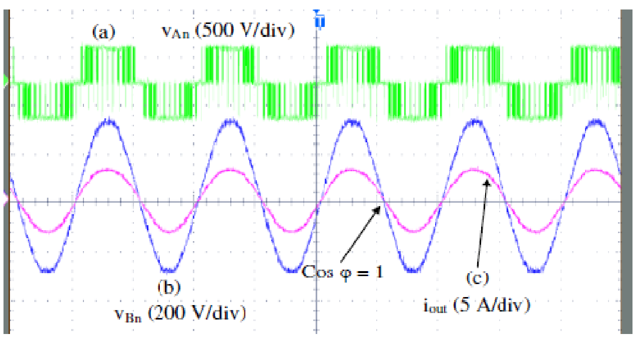

Fig. 22 Three level output voltage (V_{An}) , Output voltage (V_{Bn}), Output current (i_{out})

The Voltages across the switches S_1-S_4 are presented in Fig. 23

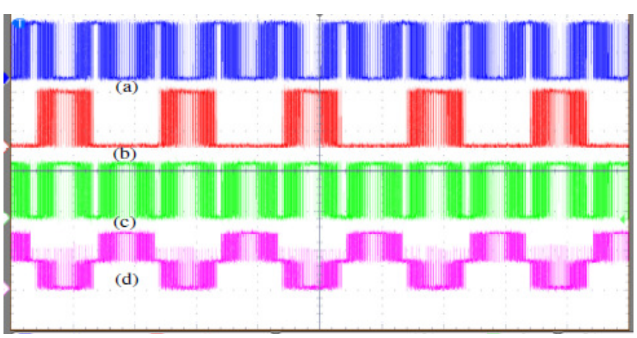

Fig. 23 Voltage across the Switches S_1-S_4

The experimentally verified results for the THD measurement of the grid current is equal to 2.1% in unity power factor operation The RMS value of the current injected to the grid is equal to 2.3 *A*, the efficiency is nearly 98% and the output power is 500 *W*.

VIII. CONCLUSION

This paper has proposed a new single phase transformerless inverter for grid tied PV system using a charge pump circuit concept. The concept is proposed to generate the negative output voltage in the proposed inverter. This new topology generates a three level output voltage by employing unipolar SPWM. The negative terminal of the proposed topology is the same as the neutral line in the grid, thus the leakage current is well suppressed and the transformer is eliminated. The proposed topology has also the ability to deliver reactive power into the grid. In addition, the proposed topology can be realized with a minimum number of components, hence a higher power density can be achieved with lower design cost. Compared to other existing transformerless topologies, the performance evicted by the proposed inverter is good. It can be concluded that the proposed topology is suitable for grid tied transformerless inverter.

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