

Improved Transformerless Inverter with Common-mode Leakage Current Elimination for a Photovoltaic Energy Conversion System

Dr. Deependra Singh

Department of Electrical engineering
Kamla Nehru Institute of Technology (KNIT)
Sultanpur, Uttar Pradesh

Rajat Sachan

Department of Electrical engineering
Kamla Nehru Institute of Technology (KNIT)
Sultanpur, Uttar Pradesh

Abstract— This paper represents the methods for elimination of common mode leakage current in the transformerless photovoltaic energy conversion system. An improved inverter circuitry is presented which works on low input same as full bridge inverter and insure the elimination of common-mode leakage current. MATLAB / SIMULINK model of both the control strategies unipolar sinusoidal pulse-width modulation (SPWM) and double- frequency SPWM is presented. The high efficiency and convenient thermal design is achieved with the help of two additional switches connected to the dc side, and also the higher frequency and lower current ripples are obtained by adopting the double-frequency SPWM, and thus total harmonic distortion of the output current is greatly reduced. The performance comparison between conventional and improved technology is also mentioned.

Keywords— Common-mode leakage current, junction capacitance, photovoltaic (PV) system, sinusoidal pulsewidth modulation (SPWM) strategy, transformerless inverter.

I. INTRODUCTION

In present scenario the grid-connected photovoltaic (PV) systems, especially the household single-phase systems, requires high efficiency, small size, light weight, and low-cost grid-connected inverters. Two configurations are used one employs line frequency transformer and other employs high frequency transformer [1].

First configuration have few drawbacks such as line frequency transformers are large in size and hard to install. Second configuration transformers are small in size because these transformers works on high frequency supply but few additional power stages are involved in these topologies which creates more complexity [1]. Consequently, the transformerless configuration for PV systems is developed to offer the advantages of high efficiency, and low cost. But this transformerless system have a safety issue of leakage current, because the removal of transformer from the grid-connected system results in direct connection between PV panel ground and grid ground. In electrical we cannot connect two circuits directly which have different ground potential we need some isolation for these type of connections. A common-mode leakage current flows through the parasitic capacitor between the PV array and the grid ground because a variable common-mode voltage is generated in transformerless grid-connected inverters [2]. The common-mode leakage current increases the system losses, reduces the grid-connected current quality, induces electro-magnetic interference, and causes personal safety problems [3].

Conventionally we use Half-Bridge or Full-Bridge inverter with sinusoidal pulse width modulation to remove this common-mode voltage. No common-mode leakage current generate in absence of common-mode voltage.

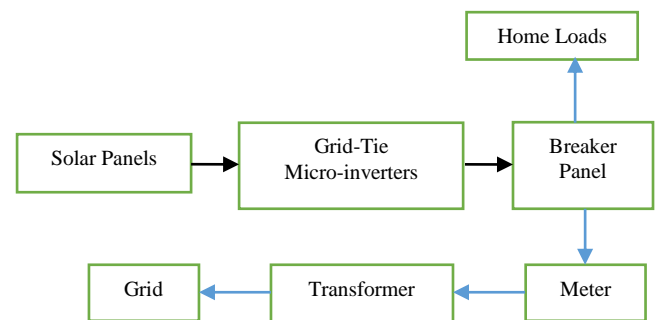


Fig.1 Basic diagram of a grid connected PV system

However, the half-bridge inverter requires a high input voltage which is greater than, approximately, 700V for 220-Vac applications [1]. That amount of voltage is generated either by applying large number of PV modules or with the help of Boost converters. The full-bridge inverter just needs half of the input voltage demanded by the half-bridge topology, which is about 350V for 220-Vac applications [1]. However both the conventional techniques are able to resolve the common mode leakage current problem but they are unable to prevent the DC injection in the grid current. This DC injection reduce the grid current quality and generate electromagnetic interferences. For resolving both the problems we need an improved inverter circuitry which not only avoid common-mode leakage current but also prevent DC injection in the grid current, this DC injection may saturate the core of main grid transformer.

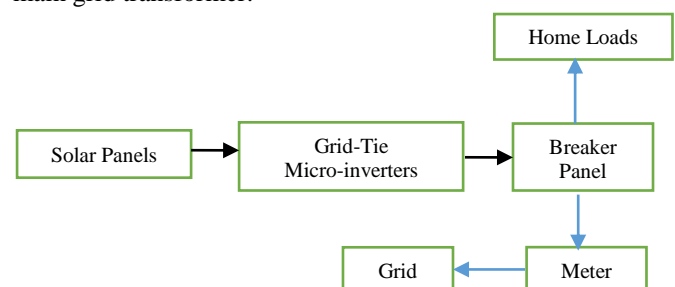


Fig.2 Basic diagram for TRANSFORMERLESS grid connected PV system

These improve inverter circuitries need the same low input voltage as the full-bridge inverter and can adopt the unipolar SPWM and bipolar SPWM strategy with three levels. These topologies are able to tackle both the problems which are mentioned above.

In this paper, an improved grid-connected inverter topology for transformerless PV systems is presented, which can sustain the same low input voltage as the full-bridge inverter and guarantee not to generate the common-mode leakage current. Furthermore, both the unipolar SPWM and the double-frequency SPWM with three-level output can be applied in the presented inverter [1]. The high efficiency and convenient thermal design are achieved by adopting the unipolar SPWM [7]. Moreover, the higher equivalent frequency and lower current ripples are obtained by using the double-frequency SPWM. Therefore, a smaller filter inductor can be employed and the harmonic contents and total harmonic distortion (THD) of the output current are reduced greatly, and the grid-connected power quality is improved accordingly [3].

II. PARACITIC CAPACITANCE AND LEAKAGE REACTANCE

PV panels are manufactured in many layers and the junction of these layers is covered by grounded metallic frame. A parasitic capacitance (stray capacitance) is formed between the earth and the metallic frame. Its value is directly proportional to the surface area of the PV panel. Dangerous leakage currents (common mode currents) can flow through the large stray capacitance between the PV array and the ground if the inverter generates a variable common mode voltage. Range of the leakage current may vary depending upon the size of the PV panel but this current has value above the safe limits, this may affect the person working in that area. These leakage currents have to be eliminated or at least limited to a safe value, and this can be done with the help of improved inverter topology.

III. CONDITION OF ELLIMINATING COMMON MODE LEAKAGE CURRENT

The ground leakage current that flows through the parasitic capacitance of the PV array is greatly influence on the common mode voltage generated by a topology. Generally the utility grid does not influence the common mode behavior of the system [14].

The common-mode voltage can be defined as the average of the sum of voltages between the outputs and the common reference. In this case, the common reference is taken to be the negative terminal of the PV. The differential-mode voltage is defined as the difference between the two voltages.

$$u_{cm} = \frac{u_{AN} + u_{BN}}{2} \quad (1)$$

$$u_{dm} = u_{AB} = u_{AN} - u_{BN} \quad (2)$$

From the above two equations,

$$u_{AN} = u_{cm} + \frac{u_{dm}}{2} \quad (3)$$

$$u_{BN} = u_{cm} - \frac{u_{dm}}{2} \quad (4)$$

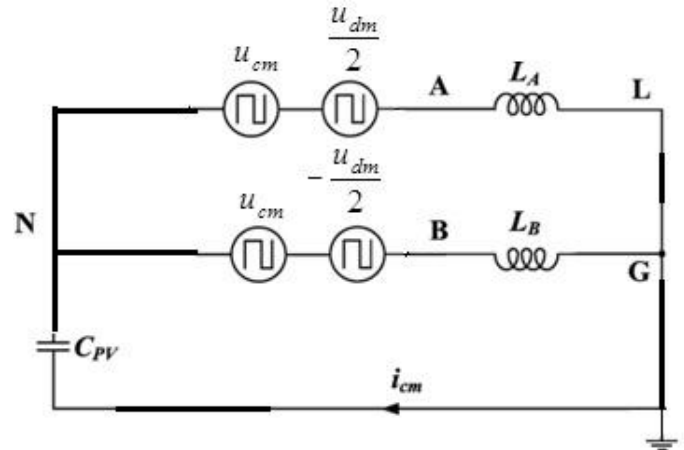


Fig.3 Model Showing the Common-Mode and Differential-Mode Voltages

Using Thevenin's theorem in the above circuit the model can be simplified. By applying Kirchhoff's voltage law in the Fig.3,

To find out current

$$-u_{cm} - \frac{u_{dm}}{2} - iL_A - iL_B + u_{cm} - \frac{u_{dm}}{2} = 0$$

$$-u_{dm} - iL_A - iL_B = 0$$

$$-u_{dm} = iL_A + iL_B$$

$$i = -\frac{u_{dm}}{L_A + L_B} \quad (5)$$

To find out the u_{ecm}

$$-u_{cm} - \frac{u_{dm}}{2} - iL_A + u_{ecm} = 0$$

$$u_{ecm} = u_{cm} + \frac{u_{dm}}{2} + iL_A$$

$$u_{ecm} = u_{cm} + \frac{u_{dm}}{2} + L_A \left(-\frac{u_{dm}}{L_A + L_B} \right)$$

$$u_{ecm} = u_{cm} + \frac{u_{dm}}{2} \frac{L_B - L_A}{L_B + L_A} \quad (6)$$

The simplified equivalent model of the common-mode resonant circuit has been derived in as shown in Figure 4, where C_{PV} is the parasitic capacitor, L_A and L_B are the filter inductors, i_{cm} is the common-mode leakage current. And, an equivalent common-mode voltage u_{ecm} is defined by,

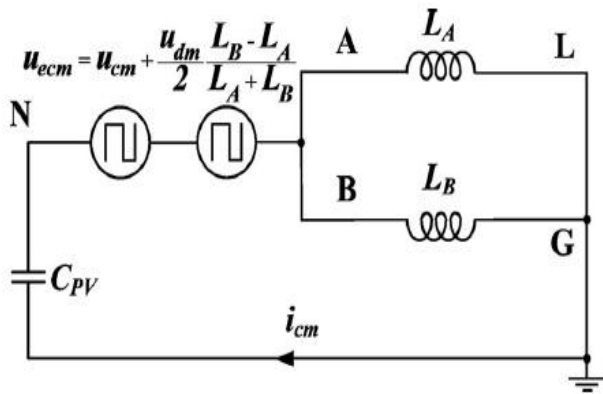


Fig.4 Simplified equivalent model of Common-mode Resonant Circuit

It is clear that the common-mode leakage current i_{cm} is excited by the defined equivalent common-mode voltage u_{ecm} . Therefore, the condition of eliminating common-mode leakage current is drawn that the equivalent common-mode voltage u_{ecm} must be kept a constant as follows,

$$u_{ecm} = u_{cm} + \frac{u_{dm}}{2} \frac{L_B - L_A}{L_B + L_A}$$

$$= \frac{u_{BN} + u_{AN}}{2} + \frac{u_{BN} - u_{AN}}{2} \frac{L_B - L_A}{L_B + L_A}$$

$$= \text{Constant} \quad (7)$$

In the full-bridge inverter family, the filter inductors L_A and L_B are commonly selected with the same value. As a result, the condition of eliminating common-mode leakage current is met that,

$$u_{ecm} = u_{cm} = \frac{u_{AN} + u_{BN}}{2} = \text{Constant} \quad (8)$$

$(L_A = L_B)$

IV. IMPROVED INVERTER TOPOLOGY AND OPERATION MODES

Improved technique can meet the condition of eliminating common-mode leakage current. In this topology, two additional switches S_5 and S_6 are symmetrically added to the conventional full-bridge inverter, and the unipolar SPWM and double-frequency SPWM strategies with three-level output can be achieved.

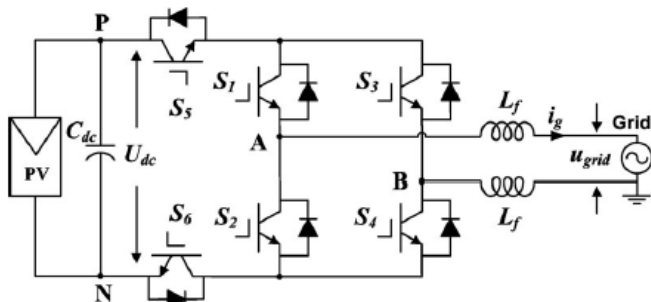
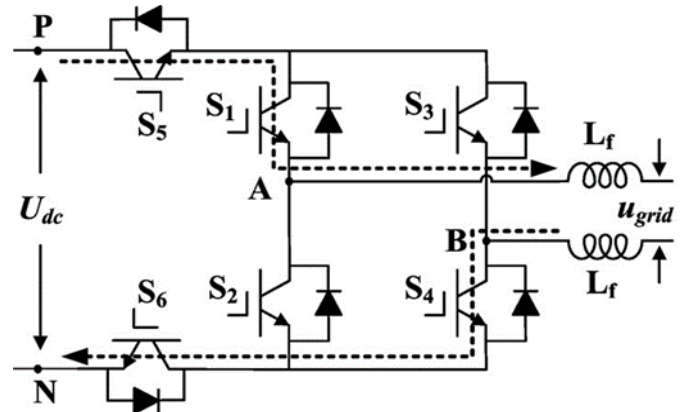


Fig.5 Improved transformerless inverter system

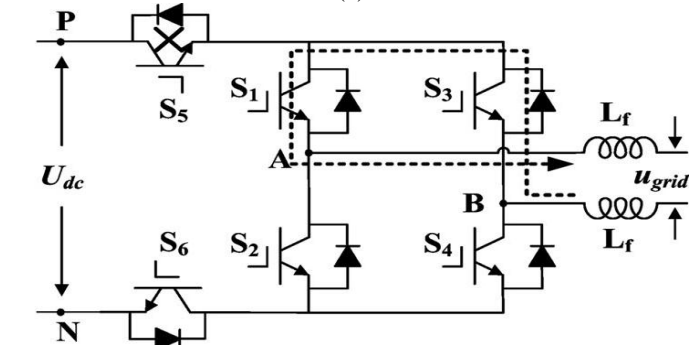
A. Unipolar SPWM Strategy

In Unipolar SPWM the common mode voltage can remain constant during all the four modes of operation. Also the switching voltages of all commutating switches are half of the input voltage, so compared with the full bridge inverter topology the switching losses are reduced. Here the switches in one phase leg operating in grid frequency, switches in another phase leg operating in switching frequency and the additional switches are operating in grid frequency and switching frequency alternately. There are four modes of operation that generate the three level output.

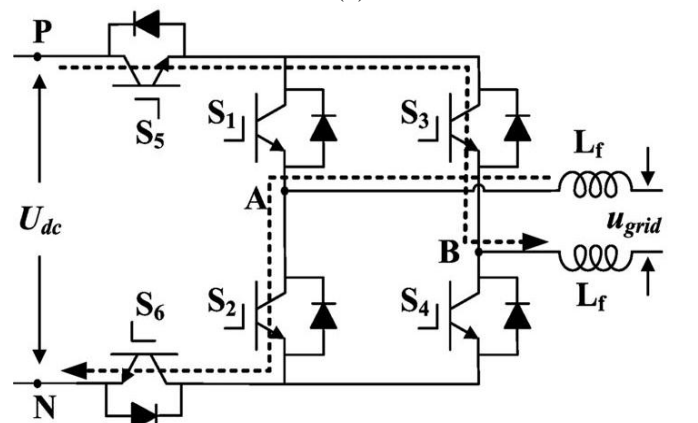
In the positive half cycle switches S_1 and S_6 are always ON and switch S_4 and S_5 commutates at switching frequency. In the negative half cycle switches S_2 and S_5 are always ON and S_3 and S_6 commutates at switching frequency.



(a)



(b)



(c)

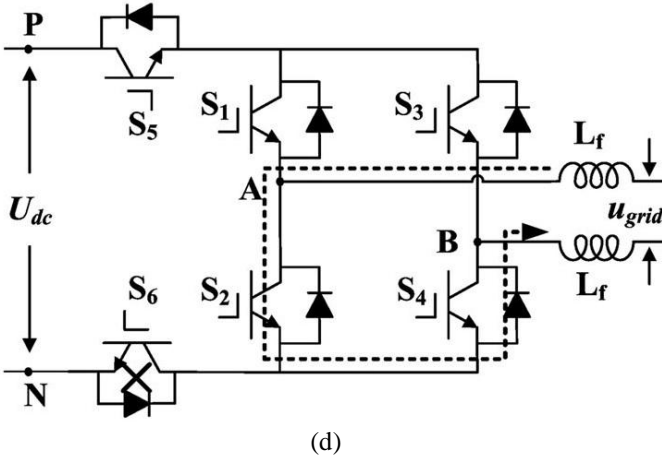


Fig.6 Operating modes of improved transformerless Inverter (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4.

Mode 1: when S_4 and S_5 are ON, $u_{AB} = +U_{dc}$ and the inductor current increases through the switches S_5 , S_1 , S_4 , and S_6 . The common-mode voltage is

$$u_{cm} = \frac{1}{2}(u_{AN} + u_{BN}) = \frac{1}{2}(U_{dc} + 0) = \frac{U_{dc}}{2} \quad (9)$$

Mode 2: when S_4 and S_5 are turned OFF, the voltage u_{AN} falls and u_{BN} rises until their values are equal, and the antiparallel diode of S_3 conducts. Therefore, $u_{AB} = 0V$ and the inductor current decreases through the switch S_1 and the antiparallel diode of S_3 . The common-mode voltage changes into

$$u_{cm} = \frac{1}{2}(u_{AN} + u_{BN}) = \frac{1}{2}\left(\frac{U_{dc}}{2} + \frac{U_{dc}}{2}\right) = \frac{U_{dc}}{2} \quad (10)$$

Mode 3: when S_3 and S_6 are ON, $u_{AB} = -U_{dc}$ and the inductor current increases reversely through the switches S_5 , S_3 , S_2 , and S_6 . The common-mode voltage becomes

$$u_{cm} = \frac{1}{2}(u_{AN} + u_{BN}) = \frac{1}{2}(0 + U_{dc}) = \frac{U_{dc}}{2} \quad (11)$$

Mode 4: when S_3 and S_6 are turned OFF, the voltage u_{AN} rises and u_{BN} falls until their values are equal, and the antiparallel diode of S_4 conducts. Similar as to **Mode 2**, $u_{AB} = 0V$ and the inductor current decreases through the switch S_2 and the antiparallel diode of S_4 .

$$u_{cm} = \frac{1}{2}(u_{AN} + u_{BN}) = \frac{1}{2}\left(\frac{U_{dc}}{2} + \frac{U_{dc}}{2}\right) = \frac{U_{dc}}{2} \quad (12)$$

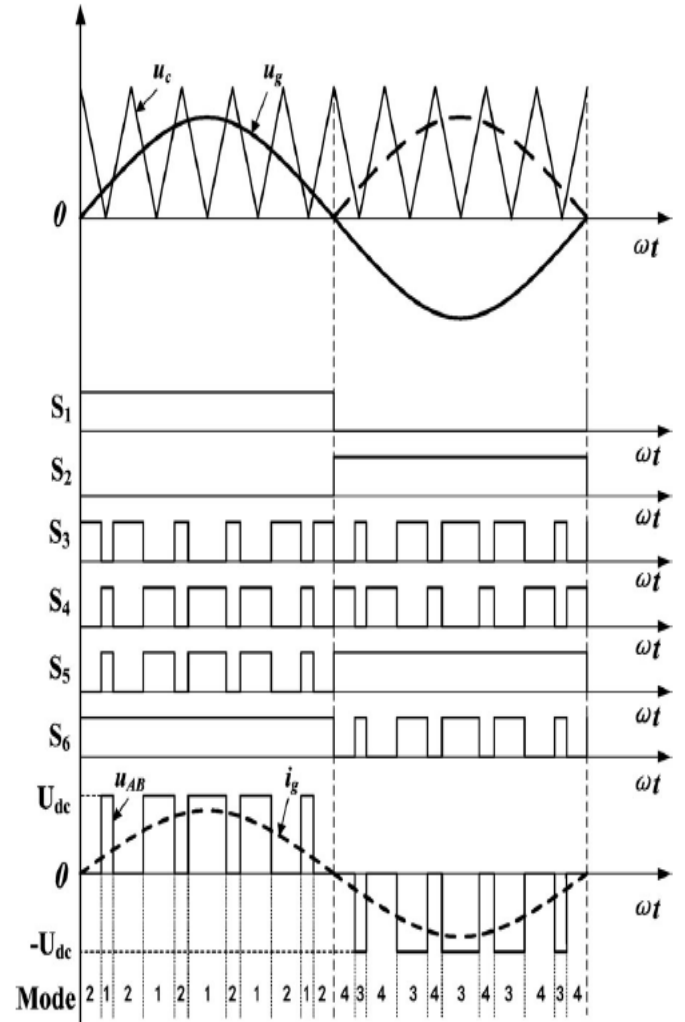
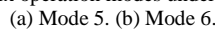


Fig.7 Ideal waveforms of the improved inverter with Unipolar SPWM

B. Double-Frequency SPWM Strategy

The improved inverter can also operate with the double frequency SPWM strategy to achieve a lower ripple and higher frequency of the output current. In this situation, both phase legs of the inverter are, respectively, modulated with 180° opposed reference waveforms and the switches S_1 – S_4 all acting at the switching frequency. Two additional switches S_5 and S_6 also commute at the switching frequency cooperating with the commutation orders of two phase legs. Accordingly, there are six operation modes to continuously rotate with double frequency and generate $+U_{dc}$ and zero states or $-U_{dc}$ and zero states, as shown in Figs. 6 and 8.

Fig. 9 shows the ideal waveforms of the improved inverter with double-frequency SPWM. In the positive half cycle, S_6 and S_1 have the same commutation orders, and S_5 and S_4 have the same orders. S_2 and S_3 , respectively, commute complementarily to S_1 and S_4 . Accordingly, **Mode 1**, **Mode 2**, and **Mode 5** continuously rotate to generate $+U_{dc}$ and zero states and modulate the output voltage with double frequency. In the negative half cycle, **Mode 3**, **Mode 4** and **Mode 6** continuously rotate to generate $-U_{dc}$ and zero states with double frequency due to the completely symmetrical modulation.


$$u_{cm} = \frac{1}{2}(u_{AN} + u_{BN}) = \frac{1}{2}\left(\frac{U_{dc}}{2} + \frac{U_{dc}}{2}\right) = \frac{U_{dc}}{2} \quad (14)$$

In the case of simulations the generated common mode voltage of the inverter topology and modulation strategy can be shown using a simple resistance as load since the utility grid has no influence on the common mode behavior of the system. The simulations were done in MATLAB/SIMULINK with switching frequency $f_{sw} = 8\text{kHz}$. To simplify the simulation the PV array was simulated with PV panel voltage $u_{dc} = 380\text{V}$. The parasitic capacitance $C_{pv} = 75\text{ nF}$, load resistance $R = 2.5\text{ k}\Omega$, filter inductances $L_f = 1.8\text{ H}$ and the filter capacitance $C_f = 2\mu\text{F}$.

A. Conventional Unipolar SPWM Strategy

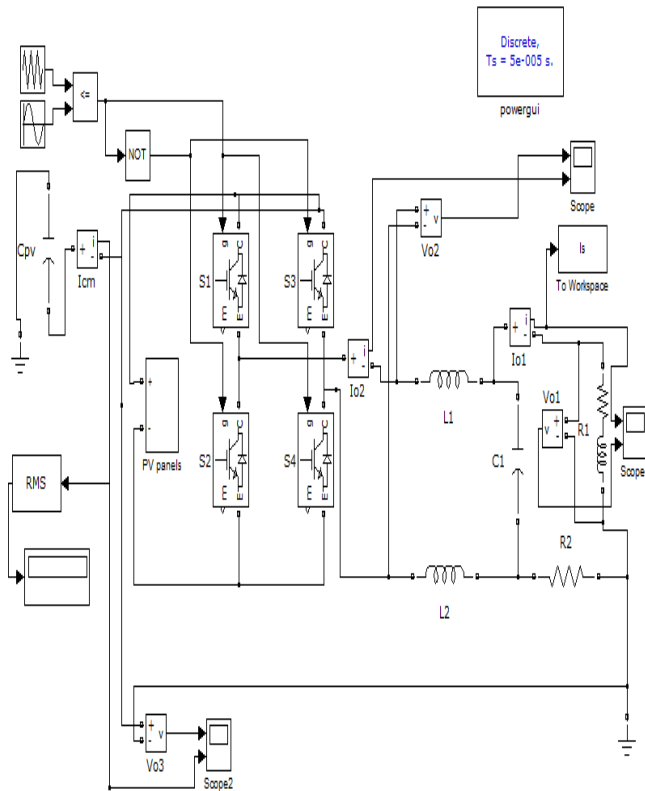
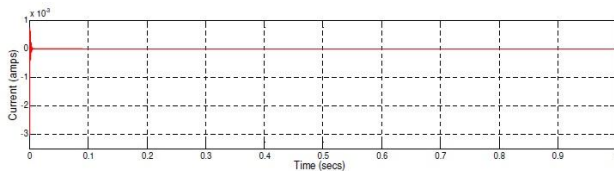
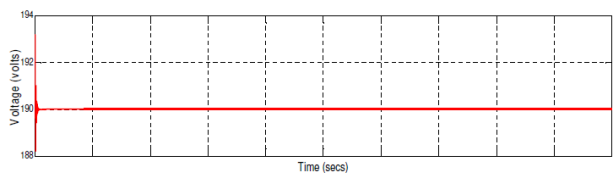


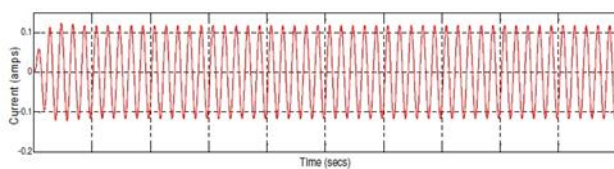
Fig.10 Simulation of transformerless PV system with conventional Unipolar SPWM



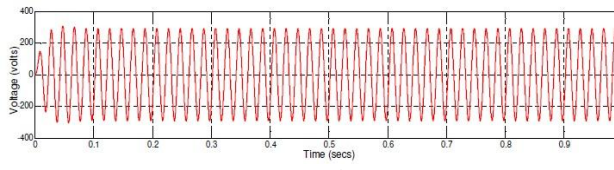
(a)



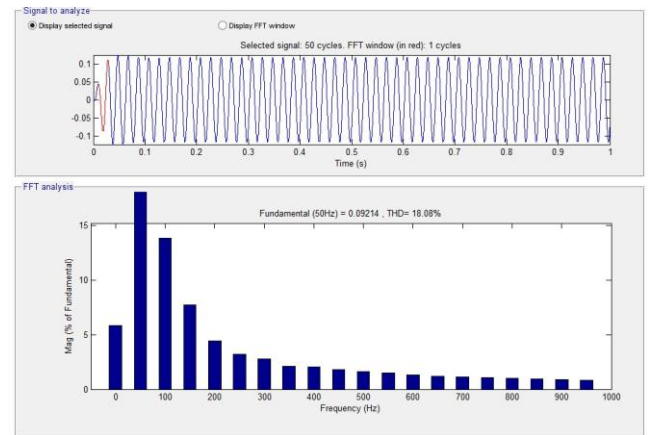
(b)



(c)



(d)



(e)

Fig.11 Simulated results by employing conventional Unipolar SPWM strategy

(a) common-mode current. (b) common-mode voltage. (c) Load current. (d) Load Voltage. (e) THD of conventional Unipolar SPWM.

B. Conventional Bipolar SPWM Strategy

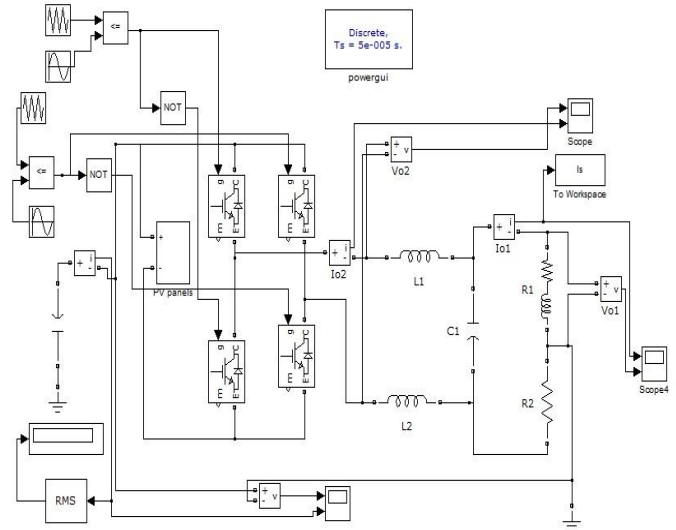
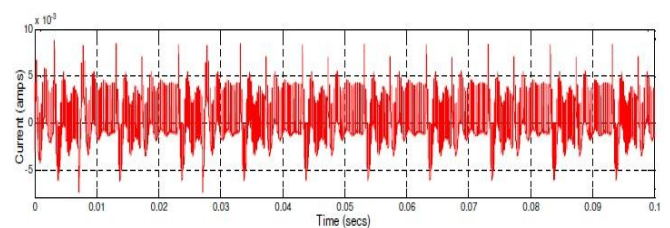
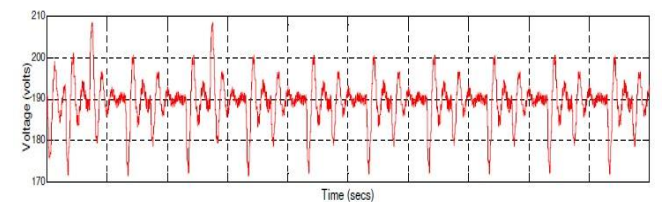


Fig.12 Simulation of transformerless PV system with conventional Bipolar SPWM



(a)



(b)

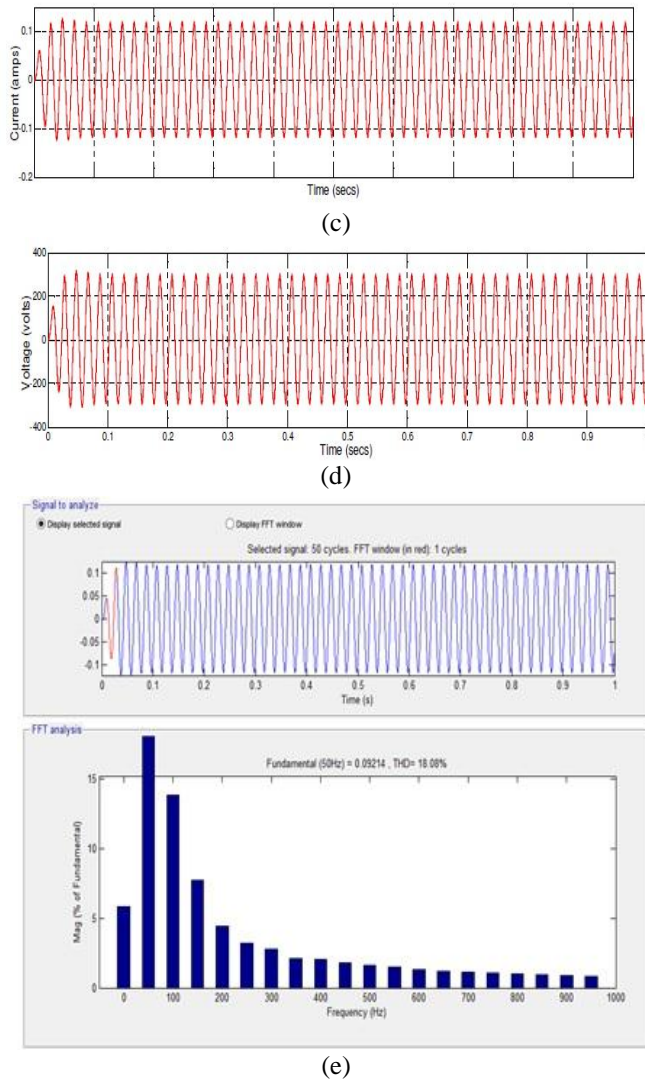


Fig.13 Simulated results by employing conventional Bipolar SPWM strategy

(a) common-mode current. (b) common-mode voltage. (c) Load current. (d) Load Voltage. (e) THD of conventional Unipolar SPWM.

C. Improved Unipolar SPWM Strategy

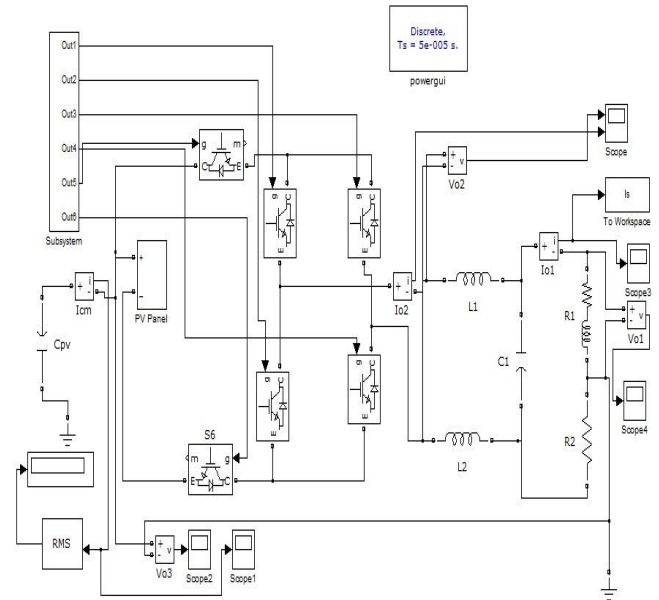
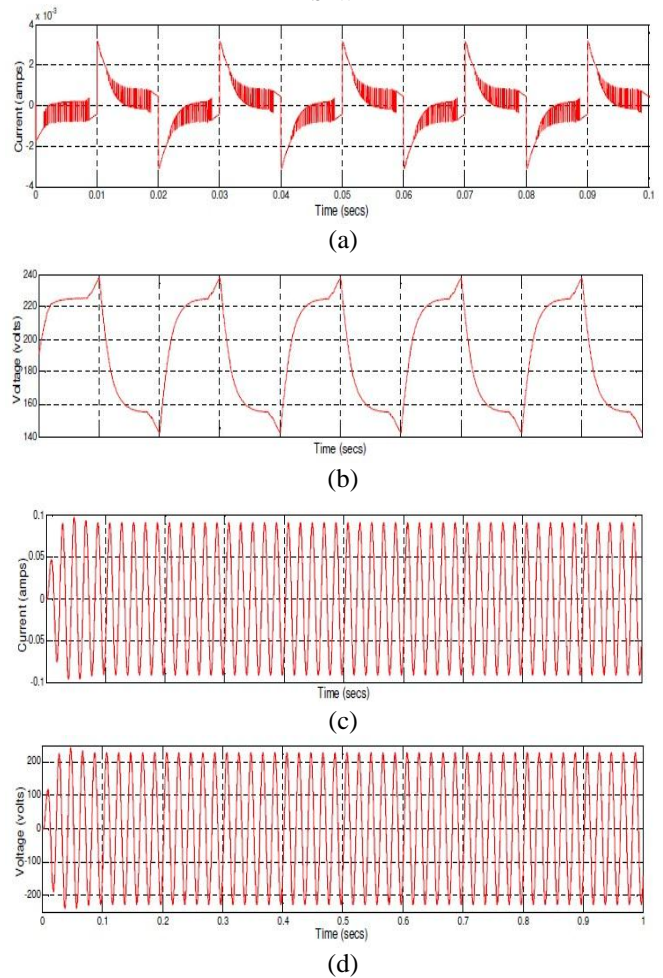
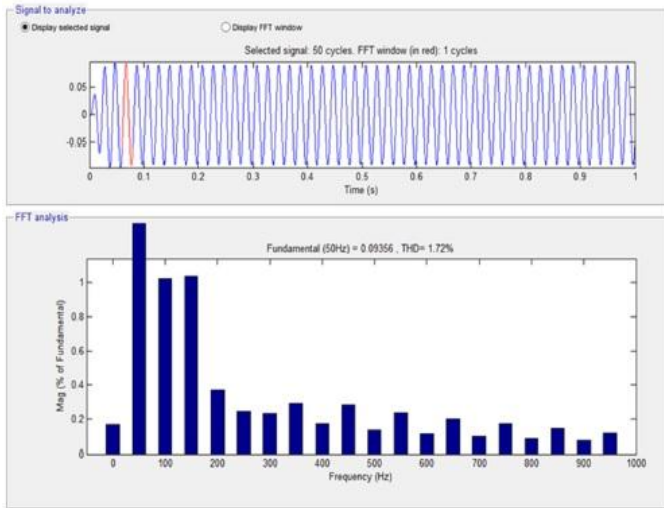


Fig.14 Simulation of transformerless PV system with improved Unipolar SPWM





(e)

Fig.15 Simulated results by employing improved Unipolar SPWM strategy

(a) common-mode current. (b) common-mode voltage. (c) Load current. (d) Load Voltage. (e) THD of conventional Unipolar SPWM.

D. Improved Bipolar SPWM Strategy

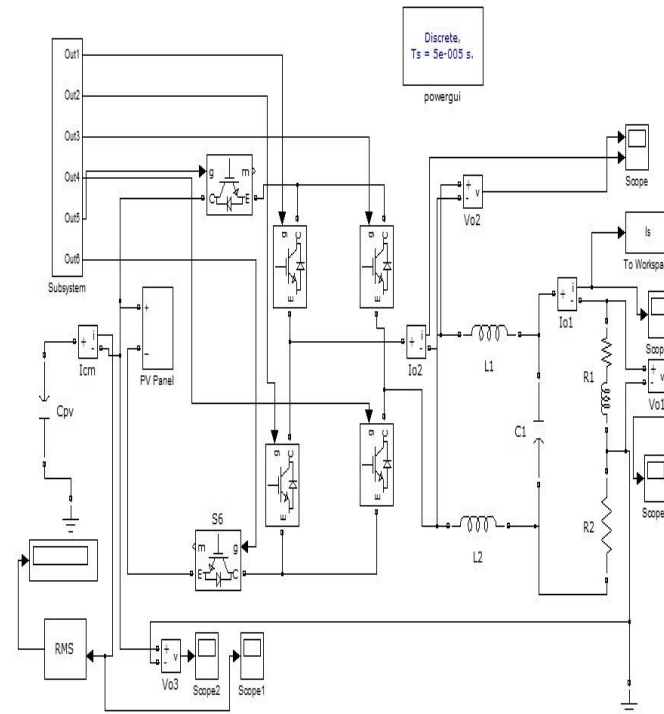
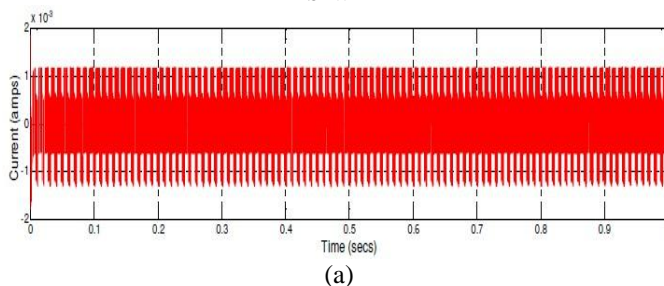
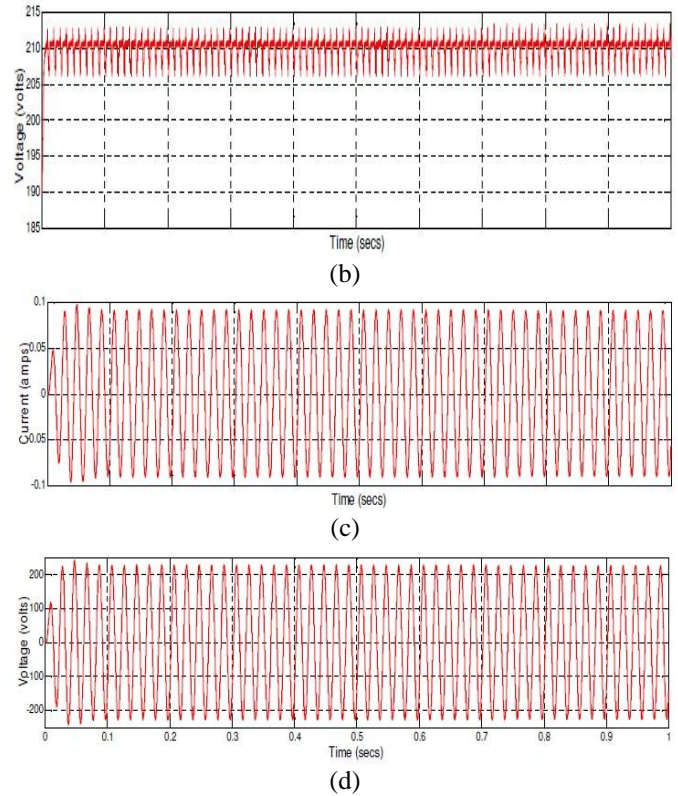


Fig.16 Simulation of transformerless PV system with conventional Bipolar SPWM



(a)



(e)

Fig.17 Simulated results by employing improved Bipolar SPWM strategy

(a) common-mode current. (b) common-mode voltage. (c) Load current. (d) Load Voltage. (e) THD of conventional Unipolar SPWM.

Table 1 Performance comparison of various methods

Systems	Conventional System		Improved System	
	Unipolar SPWM	Bipolar SPWM	Unipolar SPWM	Bipolar SPWM
Parameters				
Common mode Current (amps)	0.0005	0.0027	0.0011	0.0007
Load Current (amps)	0.11	0.12	0.08	0.08
% THD	18.08	18.07	1.72	1.51

Case wise discussion is done below –

- When we use unipolar PWM technique in half bridge or full bridge inverter common mode current minimize to microampere but there is still DC injection in grid.
- When we use bipolar PWM technique in half bridge or full bridge inverter common mode current minimize to milliampere but there is still DC injection in grid.
- When we use unipolar PWM technique in improved transformerless inverter common mode current minimize to milliampere and there is no DC injection in grid.
- When we use bipolar PWM technique in improved transformerless inverter common mode current minimize to milliampere and there is no DC injection in grid, and THD is also improved.

VI. CONCLUSION

This paper presented an improved inverter topology for transformerless PV systems. The unipolar SPWM and double-frequency SPWM control strategies are both implemented with three-level output in the presented inverter, which can guarantee –

- Not to generate the common-mode leakage current because the condition of eliminating common-mode leakage current is met completely.
- Furthermore, the switching voltages of all commutating switches are half of the input dc voltage and the switching losses are reduced greatly.
- The high efficiency and convenient thermal design are achieved thanks to the decoupling of two additional switches S5 and S6. Moreover, by adopting the double-frequency SPWM, the higher frequency and lower current ripples are achieved.
- The higher quality and lower THD of the grid-connected current are obtained, or the smaller filter inductors are employed and the copper losses and core losses are reduced accordingly.

REFERENCES

- [1] B. Yang, W. Li, Y. Gu, W. Cui, X. He, "Improved Transformerless Inverter with Common-Mode Leakage Current Elimination for a Photovoltaic Grid-Connected Power System," *Power Electronics, IEEE Transactions on*, vol.27, no.2, pp.752-762, Feb. 2012..
- [2] Yi Tang; Wenli Yao; Poh Chiang Loh; Frede Blaabjerg, "Highly Reliable Transformerless Photovoltaic Inverters With Leakage Current and Pulsating Power Elimination," *IEEE Trans. Ind. Elec.*, vol. 63, no. 2, pp. 1016-1026, 2016.
- [3] Ramin Rahimi; Babak Farhangi; Shahrokh Farhangi, "New topology to reduce leakage current in three-phase transformerless grid-connected photovoltaic inverters" *7th Power Electronics and Drive Systems Technologies Conference (PEDSTC)*, pp.421-426, 2016
- [4] Freddy Tan Kheng Suan; Nasrudin Abd Rahim; Hew Wooi Ping, "An improved threephase transformerless photovoltaic inverter with reduced leakage currents" *Clean Energy and Technology (CEAT)*, pp. 1-4, 2014