ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 3, March 2014

Leakage Current Elimination in Single Phase Transformer less Grid Connected Power Systems

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Abstract: Eliminating the leakage current is one of most important issues for transformer less inverters in grid connected photovoltaic applications. The technical challenge is how to keep the common mode voltage constant to reduce the leakage current. For this purpose an improved single phase transformer less inverter is proposed. It has two additional switches connected in the dc side. The PWM pulses for those switches are given in such a way that the condition for making the common mode voltage constant is completely met. The common mode voltage can remain a constant during all the modes in the improved inverter. Both uni polar and double frequency control strategies are applied. By adopting uni polar PWM strategy, the leakage current reduced and a higher quality and lower THD of grid connected current are obtained using double frequency PWM.

Index Terms: Common mode leakage current, improved transformer less inverter, Photovoltaic (PV) systems, Sinusoidal pulse width modulation (SPWM) strategy,

I. INTRODUCTION

In recent years, the interest for renewable energy has been significantly increased as a result of the growing energy demand, mounting power prices and the increasing need for more environmentally friendly energy sources. Renewable energy sources like solar, wind or hydro have the advantage that the power is produced in close proximity to where it is consumed. This way the losses due to transmission lines are not present. Among various types of renewable energy sources, solar energy has become the most promising and commercially attractive in recent years, being cleaner and more environmentally friendly energy resource. The ease of installation and declining cost of technology has led solar PV energy to become one of the leading renewable energy sources.

One of the major advantages of PV technology is that it has no moving parts. Therefore, the hardware is very robust, it has a long lifetime and low maintenance requirements. And most importantly, it is one solution that offers environmentally friendly power generation [1]. In general, the PV systems are classified into two different groups: stand-alone PV systems (off grid) and grid-connected systems. Stand-alone PV systems operate independent of the electric utility grid. Grid-connected PV systems are designed to operate in parallel with the electric utility grid. In earlier times, stand-alone PV systems were most common. However, significant price reductions of PV modules and power conversion technology improvements have led to an increase in the up taking of grid-connected PV systems.

Grid connected PV power system usually consists of a solar panel and a power conversion unit. The inverter can achieve the maximum power point tracking (MPPT) of the solar panels and inject a sinusoidal current into the grid [2]. The grid connected inverters are classified in to two based on the electrical isolation between the PV panel and the electrical utility; grid connected inverters with galvanic isolation and without galvanic isolation. Galvanic isolation is done either by using a high frequency transformer at the grid side or a low frequency transformer on the dc side of inverter.

In order to increase the efficiency and to reduce the size and cost of grid connected power systems, the effective solution is to remove the isolation transformer. But it leads to the appearance of common mode leakage current due to the presence of parasitic capacitance between the PV panel and the ground. The common-mode leakage current flows via parasitic capacitance of the panel to the system which is not meant to be energized. It causes personal safety problems, degradation in panels, system losses, reduces the grid-connected current quality and induces the severe conducted and radiated electromagnetic interference.

In order to avoid the common-mode leakage current, the conventional method is to employ the half-bridge inverter or the full-bridge inverter with bipolar sinusoidal pulse width modulation (SPWM), because no variable common-mode voltage is generated [1]. However, the half-bridge inverter requires a high input voltage. As a result, either large numbers of PV modules in series are required or a boost dc/dc converter with extremely high-voltage conversion ratio should be used as the first power processing stage. The full-bridge inverter just needs half of the input voltage demanded by the half-bridge topology. But the main drawback is that the full bridge inverter cannot employ uni polar SPWM strategy with three levels since it generates a variable common mode voltage. It can only employ the bipolar SPWM strategy with two levels, which induces high current ripple, large filter inductor, and low system efficiency [1]

II. PARASITIC CAPACITANCE AND LEAKAGE CURRENT

PV panels are manufactured in many layers and the junction of these layers is covered by grounded metallic

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ISSN (Print) 2321 – 5526

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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. These leakage currents have to be eliminated or at least limited to a safe value.

III. CONDITION OF ELIMINATING THE 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 behaviour of the system [4].

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.

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

From the above two equations,

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

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

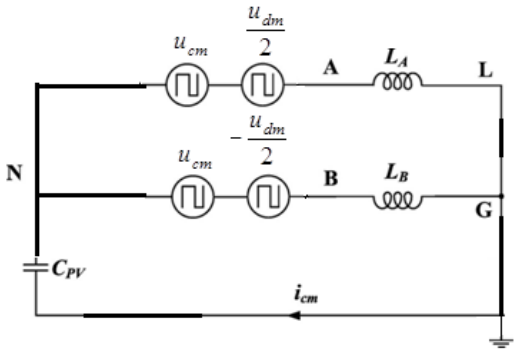

Fig1: Model Showing the Common-Mode and Differential-Mode Voltages.

Using Thevenin's theorem in the above circuit the model can be simplified. By applying Kirchhoff's voltage law in the Fig.1,

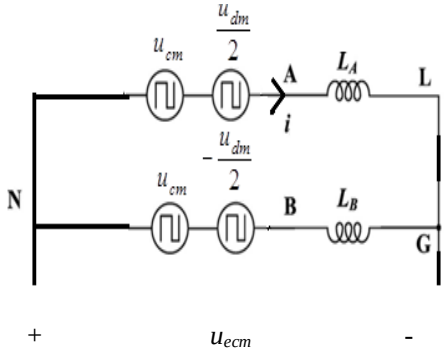

Fig2: Model to find out the Equivalent Common-Mode Voltage.

To find out the current,

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

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

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

$$-u_{dm} = i(L_A + L_B)$$

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

To find out the u_{ecm}

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

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

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

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

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

The simplified equivalent model of the common-mode resonant circuit has been derived in as shown in Figure 6.3, 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,

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

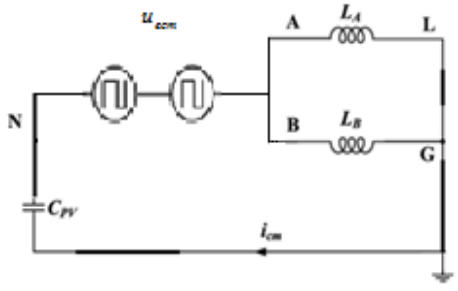

Fig3: Simplified equivalent model of Common-mode Resonant Circuit

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,

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INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
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$$u_{ecm} = u_{cm} + \frac{u_{dm}}{2}\frac{L_B - L_A}{L_A + L_B}$$
$$= \frac{u_{AN} + u_{BN}}{2} + \frac{u_{AN} - u_{BN}}{2}\frac{L_A - L_B}{L_A + L_B}$$
$$= \text{constant} \quad \text{.....(7)}$$

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,

$$u_{ecm} = u_{cm} = \frac{u_{AN} + u_{BN}}{2} = \text{constant}$$
$$(L_A = L_B) \text{...(8)}$$

IV. THE PROPOSED SYSTEM

The improved inverter topology consists of two additional switches connected symmetrically in the conventional full bridge inverter. The condition for eliminating the common mode current is guaranteed in this topology. The PWM pulses to those switches are given in such a way that the above derived condition is completely met. Both the uni polar SPWM and double-frequency SPWM strategies are adopted and the three-level output are achieved.

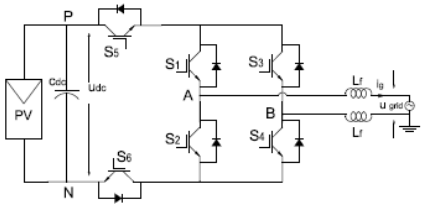
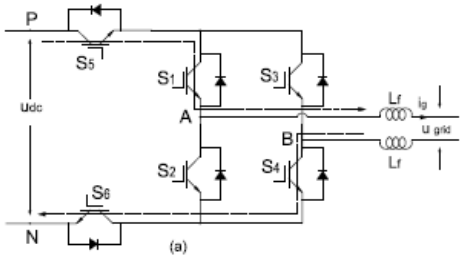


Fig4: Improved transformer less inverter system

A. *Uni polar SPWM Strategy*

In uni polar 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 S1 and S6 are always ON and switch S4 and S5 commutates at switching frequency. In the negative half cycle switches S2 and S5 are always ON and S3 and S6 commutates at switching frequency.



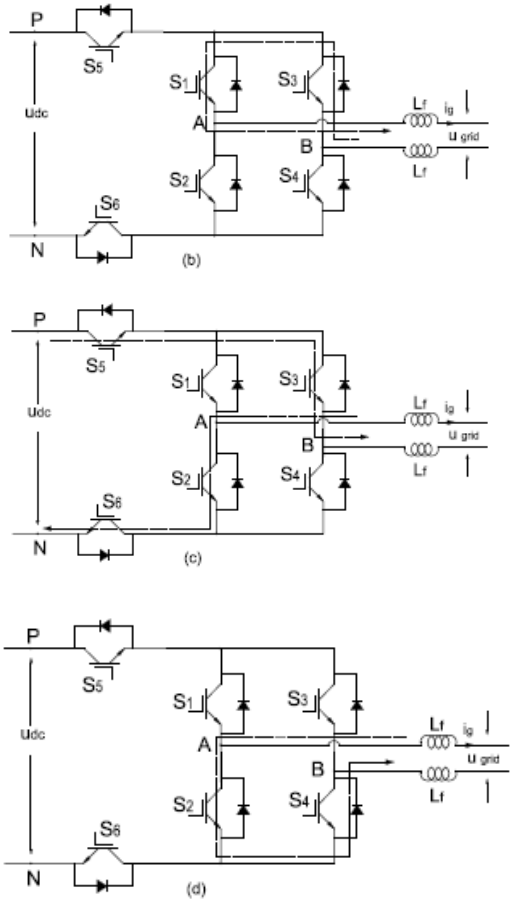


Fig5: Operating modes of improved transformer less inverter (a) Mode 1. (b) Mode 2.(c) Mode 3.(d) Mode 4

Mode 1: During positive half cycle when S4 and S5 are ON the inductor current increases through S5, S1, S4 and S6.Then,

$$u_{AN} = u_{dc},$$
$$u_{BN} = 0,$$
$$u_{AB} = \frac{u_{AN} + u_{BN}}{2},$$
$$u_{cm} = \frac{u_{AN} + u_{BN}}{2} = \frac{u_{dc}}{2} \text{.....(9)}$$

Mode 2: During mode 2 switches S4 and S5 are turned OFF, the voltage u_{AN} falls and the voltage u_{BN} rises until their values are equal. The anti parallel diode D3 across the switch S3 conducts. The current decreases through the path S1, D3.

$$u_{AN} = \frac{u_{dc}}{2}$$
$$u_{BN} = \frac{u_{dc}}{2}$$
$$u_{AB} = u_{AN} - u_{BN} = 0$$
$$u_{cm} = \frac{u_{AN} + u_{BN}}{2} = \frac{u_{dc}}{2} \text{.....(10)}$$

Mode3: During negative half cycle when S3 and S6 are

ISSN (Online) 2321 – 2004
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ON the inductor current increases reversely through the switches S5, S3, S2 and S6.Then,

$$u_{AN} = 0, u_{BN} = u_{dc}$$

$$u_{AB} = -u_{dc}$$

$$u_{cm} = \frac{u_{AN} + u_{BN}}{2} = \frac{u_{dc}}{2} \quad \text{.....(11)}$$

Mode4: When S3 and S6 are OFF, The voltage u_{AN} rises and the voltage falls until $u_{AN} = u_{BN}$ .The anti parallel diode of S4, D4 conducts and the inductor current decreases through switch S2 and diode D4.Then,

$$u_{AN} = \frac{u_{dc}}{2}, u_{BN} = \frac{u_{dc}}{2}$$

$$u_{AB} = 0$$

$$u_{cm} = \frac{u_{dc}}{2} \quad \text{.....(12)}$$

B. Double frequency SPWM Strategy

By adopting double frequency SPWM strategy the lower ripples and higher frequency of the output current are achieved. In this strategy all switches are working at the switching frequency. There are six operation modes to generate the three states.

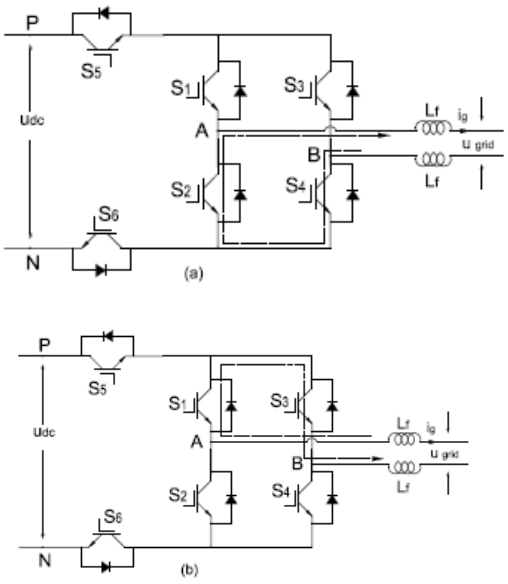


Fig6: Remaining modes of operation
(a) Mode 5.(b) Mode 6.

Mode 5: This mode comes just after Mode 1 in the positive half cycle. When S1 and S6 are OFF u_{AN} falls and u_{BN} rises until $u_{AN} = u_{BN} = \frac{u_{dc}}{2}$ and the anti parallel diode D2 of S2 conducts. Then,

$$u_{AB} = 0$$

$$u_{cm} = \frac{u_{dc}}{2} \quad \text{.....(13)}$$

Mode 6: This mode comes just after Mode 3 in the negative half cycle. When S2 and S5 are turned OFF, similar to Mode 5 the voltage u_{AN} rises and the voltage u_{BN} falls until their values are equal and the antiparallel diode D1 of S1 conducts. The inductor current decreases through the switch S3 and the diode D1.Then,

$$u_{AB} = 0$$

$$u_{cm} = \frac{u_{dc}}{2} \quad \text{.....(14)}$$

Thus in all the modes of operation the common mode voltage remains a constant.

V. SIMULATION RESULTS

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 behaviour of the system. The simulations were done in Matlab Simulink with switching frequency f_{sw} =8kHz.To simplify the simulation the PV array was simulated with DC source voltage u_{dc} =380V.The parasitic capacitance C_{pv}=75 nF, load resistance R=7.5 Ω, filter inductances L_f=1.8 H and the filter capacitance C_f=2μH.

A. Conventional uni polar SPWM Strategy

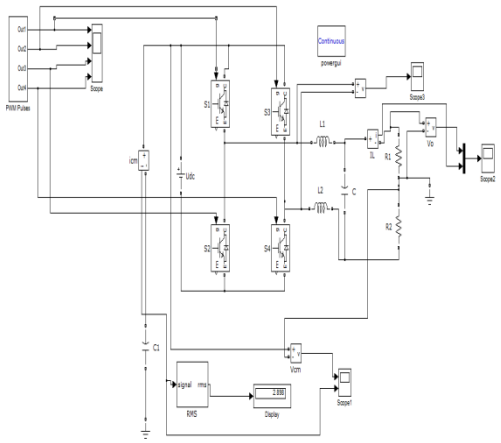
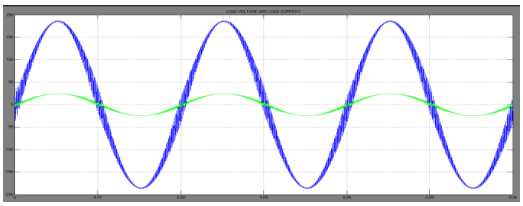
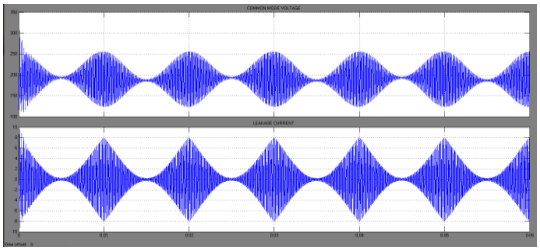


Fig.6.Simulated circuit diagram of conventional uni polar SPWM strategy



(a)



(b)

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ISSN (Print) 2321 – 5526

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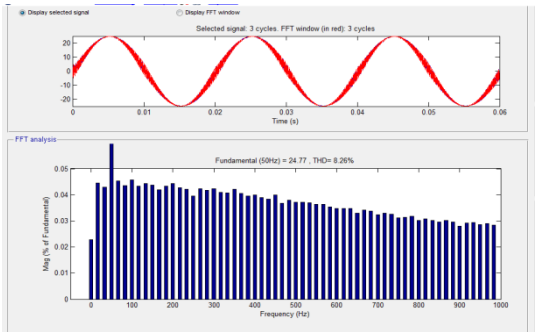


(c)

Fig.6. Simulated results by employing conventional uni polar SPWM strategy.

(a) Load voltage and load current. (b) Common mode voltage and leakage current. (c) Load current THD.

B. Improved Uni polar SPWM Strategy

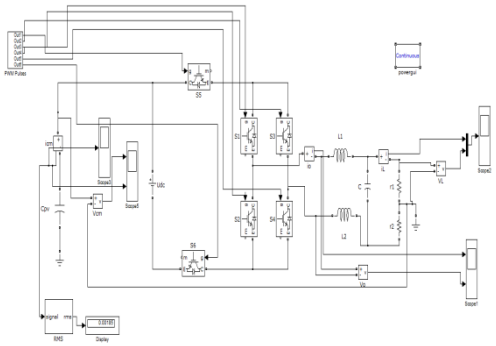
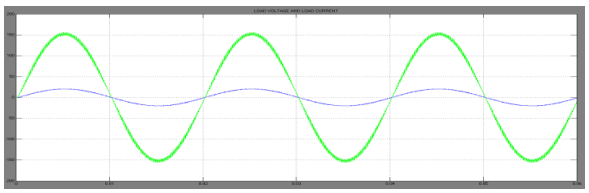


Fig.7.Simulated circuit diagram of improved uni polar SPWM strategy



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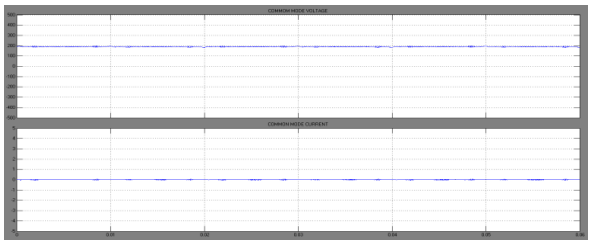

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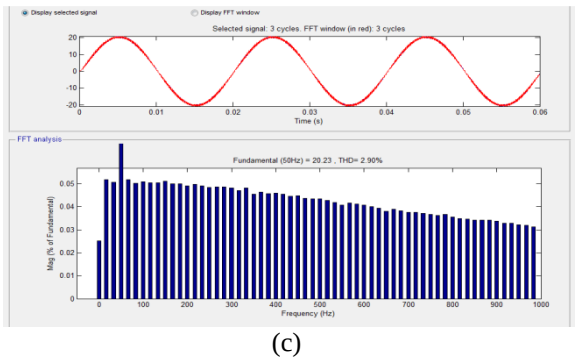


(c)

Fig.8. Simulated results by employing improved uni polar SPWM strategy. (a) Load voltage and load current. (b) Common mode voltage and leakage current. (c) Load current THD.

C. Improved Double Frequency SPWM Strategy

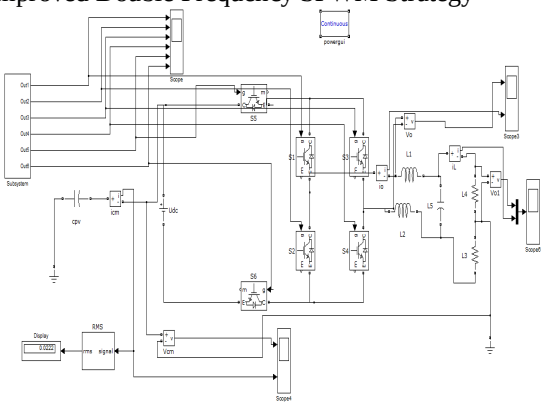
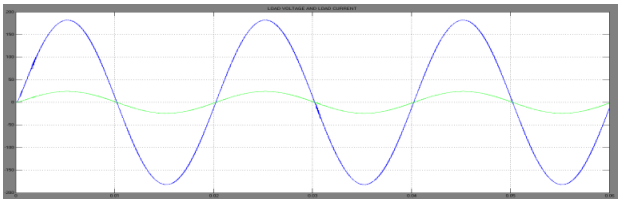


Fig.7.Simulated circuit diagram of improved uni polar SPWM strategy



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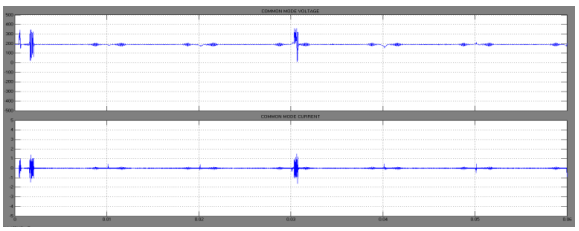

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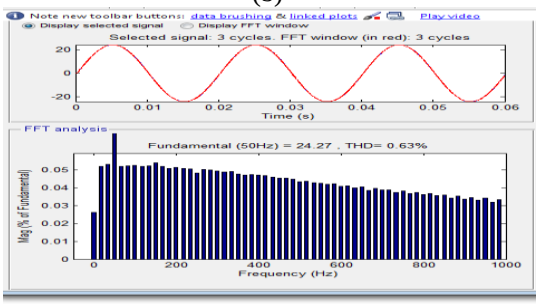

(c)

Fig.8. Simulated results by employing improved double frequency SPWM strategy. (a) Load voltage and load current. (b) Common mode voltage and leakage current. (c) Load current THD.

VI. CONCLUSION

Common mode leakage current problem in transformer less inverter is solved using the improved transformer less inverter. The improved topology has two additional switches connected in the dc side of the inverter. Both uni polar and double frequency PWM methods are implemented. The PWM pulses are given in such a way that the condition for eliminating common mode current is

completely met. In conventional system leakage current is 2.8 A and current THD is 8.26%. By adopting improved uni polar PWM topology leakage current reduced to 1.85 mA with output current THD=2.9% whereas for double frequency PWM even though the value of leakage current obtained is more than that of uni polar (22.2 mA), the output current THD is greatly reduced to 0.69%.Thus higher frequency and lower current ripples are using double frequency PWM. Thereby higher quality and lower THD of grid connected current are obtained. The simulation results obtained using Matlab Simulink.

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