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Reduction of Common Mode Leakage Current in Three Phase Transformerless Photovoltaic Grid Connected System

***Abstract**. The Photovoltaic (PV) based power generation systems are popular nowadays. In this PV based systems the voltage stress across the power devices and leakage current are the major issues in transformer-less grid connected photovoltaic system. To overcome the above drawbacks a Modified T-Source Inverter (MTSI) based single stage transformerless grid connected photovoltaic(PV) system is presented in this paper. MTSI has the advantages of low leakage current, reduced voltage stress, less passive components and no shoot through problem compared to other type transformers grid connected inverter system. The analytical model of leakage current of MTSI based grid connected PV system is derived and simulated using MATLAB Simulink. The simulated results are compared with Improved z-source inverter(IZSI) using modified space vector pulse width modulation scheme(MSVPWM).Finally the performance of MTSI based system experimentally verified; it shows the satisfactory operation in a grid connection mode.*

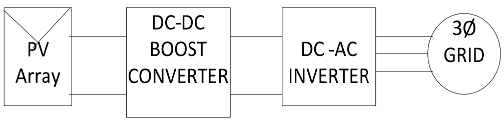
***Streszczenie.** W artykule opisano zmodyfikowany przekształtnik umożliwiający redukcję prądu upływu w trójfazowym beztransformatorowym układzie fotowoltaicznym podłączonym do sieci. Przedstawiono model analityczny systemu oraz jego symulację. Właściwości układu zbadano tez eksperymentalnie. (**Redukcja prądu upływy w trójfazowym beztransformatorowym układzie fotowoltaicznym podłączonym do sieci**)*

Keywords: Single stage power conversion, Transformerless grid connected inverter, leakage current, Photo voltaic systems..
Słowa kluczowe: przekształtnik beztransformatorowy, układ fotowoltaiczny.

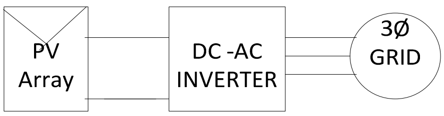
Introduction

The usage of distributed generation renewable sources such as solar energy, wind energy and fuel energy become more popular because of environment friendly and increasing demand of electric energy, which had been described in [1].Power electronics converter and inverter (power conditioning unit) plays an important role in connecting distributed generation to the grid supply [2-13].

There are two types of universal power conversion process available to convert renewable energy into grid supply such as (i) single stage conversion (ii) two stage conversion. The single stage conversion is achieved by using only one inverter and it is used to convert the DC input supply to AC supply for grid connected systems. In two stage process does-DC and DC-Ac conversion is possible as shown in fig. 1.



(a)Two stage Conversion



(b) Single stage Conversion

Fig.1 Transformerless grid connected system

Both conversion systems had their own merits and demerits when comparing compact and cost effective the single stage conversion is more efficient than two stage conversion process as stated in [14]. Now-a-days there are several single stage converters is proposed for grid connected conditioning unit, which have the following characteristics:

(1) Output voltage regulation for wide variation in the output voltage of renewable energy source (like fuel cell, PV) (2) Capability for standalone and grid connected operations (3) Low output harmonics (4) Higher energy conversion efficiency [15]. In addition to that the power conversion inverter should process no common mode voltage problems, less input current ripple and no shoot through problem, resonance problems, boost-buck the input voltage as required to grid voltage level with a good dynamic response.

The conventional inverter had shoot through and over voltage problem. FZ Peng has proposed a single stage buck boost converter called a Z - source inverter [16]. It had the advantage to handle the shoot through problem and it requires two inductors and capacitors. It creates a resonant problem and inrush current problem. To overcome the inrush and resonant problem Yu Tang (2011) proposed an improved Z-source inverter [17], which had more reactive component and less compact compared to T-source inverter. The T-source inverter was proposed in (2009) [18] which has the less reactive components, compact, high efficiency and has a good dynamic response to the above mentioned one.

The common mode leakage current is a major issue in Transformerless grid connected system. It increases the power loss and reduces the grid current quality [21].So the designer must follow the DIN V VDE V 0126-1-1 standard while designing the transformerless grid connected PV system. This standard describe the common mode leakage current less than 300mA for grid connected PV system. The controlling of leakage current is very essential to improve the system efficiency.

In this paper a new single phase modified T source inverter (MTSI) for tranformerless grid connected PV system is proposed. It has the advantages of low reactive components, boost and buck the input voltage to the required level, reduced leakage current, less voltage stress across the switches, high efficiency and compact. Moreover MTSI performance is compared with IZSI with MSVPWM scheme.

System Description:

This paper proposes a single stage modified TSI based PV fed grid connected systems as shown in fig. 2. Which consists of the PV array, modified T-Source inverter, LCL filter and grid. The PV array is supported by grounding structure which forms a path for the leakage current flow it is mentioned by an equivalent electrical component of stray capacitance (C_{pv}) and ground resistance (R_g). Modified T source inverter (MTSI) consists of conventional TSI with one extra diode in the negative terminal of DC bus and it is controlled by modified space vector pulse width modulation scheme (MSVPWM). LCL filter used to control the high frequency switching harmonics injected by the inverter and final grid is connected grid voltage was taken as feedback to control the inverter.

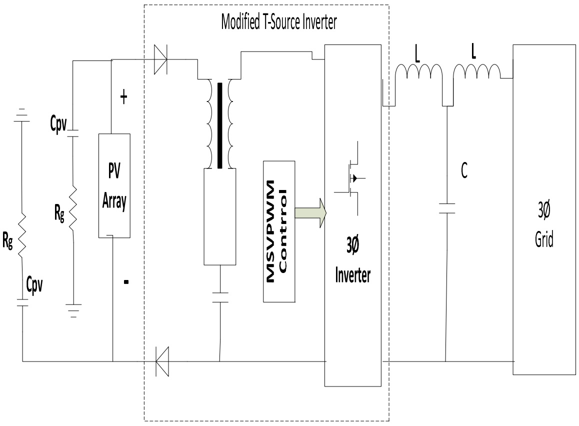


Fig 2.Proposed single stage PV fed grid connected systems.

Common mode voltage in MTSI

Common mode voltage of three phase transformer less z source inverter for PV based grid connected system has been discussed [18-20] and based on the equation presented there the common mode voltage (CMV) of MTSI can be calculated in same manner. The proposed method is a transformer less grid connected system. There is possibility to flow of leakage current to ground from a PV panel because of a galvanic connection between PV cell and grid.

The common mode voltage (CMV) of three phase inverter can be calculated [20].

$$v_{CM} = \frac{v_{An} + V_{Bn} + v_{Cn}}{3}$$

The common mode voltage of inverter with refer to negative terminal is expressed as

$$v_{Nn} = -\frac{v_{An} + V_{Bn} + v_{Cn}}{3}$$ h---------------{*}

The common mode circuit of MTSI is shown in fig.3 which includes PV array stray capacitance(C_{pv}) , filter inductance(L_f) with their internal resistances (R_f), and resistance between the ground connection of the PV array frame and the grid, inductance between the ground connection of the inverter and the grid (L_{cg}).

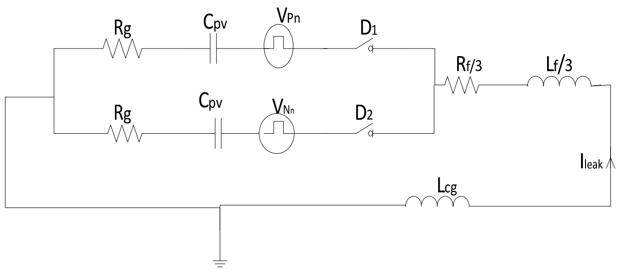


Fig.3 Common mode circuit of MTSI

Modified T-source inverter operates in two modes namely shoot through zero mode and non shoot through mode (active mode)using MSVPWM technique. So it is necessary to find the common mode voltage in two modes as follows.

Shoot through mode:

In the shoot through the mode of MTSI occurs when any one of the shoot through zero state in seven of its, during which positive and negative group of switches of one or more phase legs are turned on and the equivalent circuit is shown in fig.4 at that time both diodes D1 and D2 are reversed biased inverter circuit is disconnected from the source. The Same time capacitor charges the inductor. The leakage voltage can be calculated using {*} as the voltage across L_1 and L_2 are $V_{L1}= V_{PN}+V_C$ $V_{L2}=V_{L1}= V_L$; $V_{D1} =V_{D2}=V_D$

(1) $$v_{Nn} = -(2v_L + v_D)$$

(2) $$v_L = v_C = B_f * v_{PN}$$

(3) $$v_D = \frac{v_{PN} - 2v_L}{2}$$

where: $B_f = \dfrac{1}{1-2D_{sh}}$

B_f-boost factor, D_{sh}-shoot through duty ratio substituting (3)&(2) in(1)

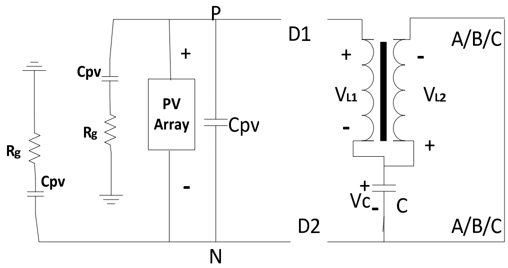


Fig.4 Shoot through mode and shoot through the mode of MTSI

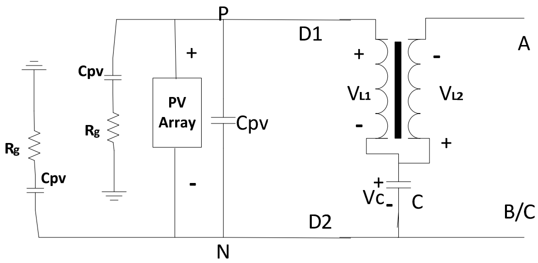


Fig.5 Non shoots through mud and shoot through the mode of MTSI

Non shoot through mode (active mode):

MTSI in any one of its six active switching states for an interval of (1-D_{sh}) is said to be an active mode of operation. The equivalent circuit of the MTSI as shown fig.5 Using equation {*} we can find the leakage voltage V_{Nn}

$V_{L2} = -V_c$; $V_{L1} = V_{L2} = -V_c$

$$v_{Nn} = -\frac{(v_{PN} - 2v_L + 2v_L + 2v_L)}{3}$$

$$v_{Nn} = -\frac{(2v_L + v_{PN})}{3}$$

(6)

Inductor voltage V_L is found

(7)

$$v_L = v_{PN} - v_C = v_{PN} - B_f * v_{PN} = (1 - B_f) * v_{PN}$$ w

here $B_f = \dfrac{1}{1-2D_{sh}}$

Now submitting (7) in (6) we get leakage voltage for non shoot through mode(8)

$$v_{Nn} = -\frac{(2(1 - B_f) * v_{PN} + v_{PN})}{3}$$

$$v_{Nn} = -v_{PN}\frac{(3 - 2B_f)}{3}$$

(8)

Voltage Stress of MTSI:

For three phase T source inverter voltage stress is $V_s = (\sqrt{3}G - 1) \times V_{dc}$ and voltage gain

$G = M_i \times B_f$ again the boost factor

$$B_f = \frac{1}{1-(n+1)D_{sh}}$$

where n turns ratio of coupled inductor and D_{sh} Shoot through duty ratio of MTSI and M_i is modulation index. The high voltage gain of MTSI was obtained by proper value shoot through duty ratio (D_{sh}) and turns ratio (n).Fig.6 shows the comparison of TSI and ZSI with respect to gain and voltage stress. It is clearly showing the same voltage stress MTSI gives a high gain compares to ZSI.

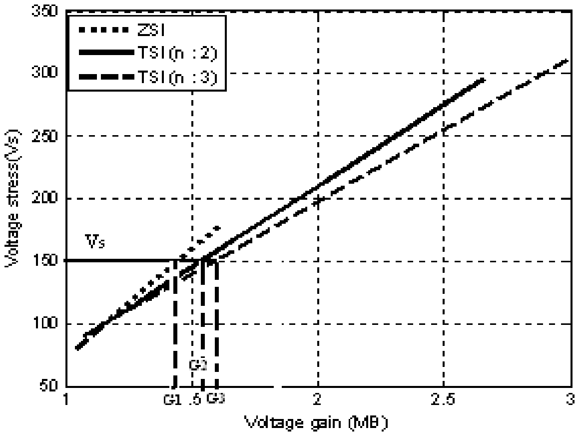


Fig.6 Voltage stress and voltage gain comparison of MTSI and improved ZSI

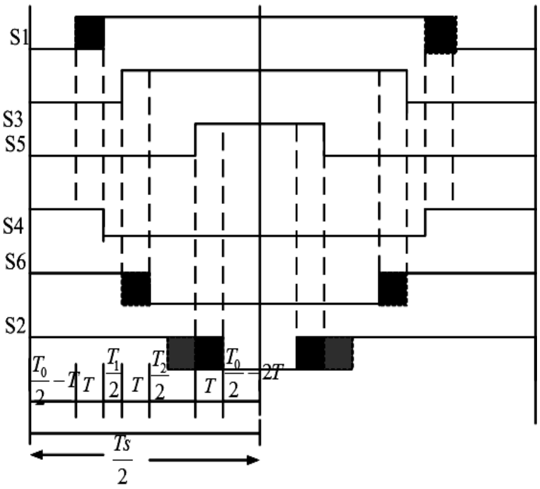


Fig.7 Pulse pattern for sector: I

Control Algorithms for Modified TSI:

The common mode voltage is controlled by proper configuration of the inverter and suitable pulse width modulation scheme of the inverter. In this paper modified space vector pulse width modulation (MSVPWM) is used for control the MTSI. The MSVPWM was presented for z-source inverter [21, 22]. This MSVPWM has an additional shoot through time T_{sh} for boosting the dc link voltage of the inverter beside time intervals T_1,T_2 and T_0 . So the shoot through problem was handled in a positive manner. Within a zero voltage period(T_0) the shoot through time periods are evenly distributed to $T_{sh}/6$ for each phase it does not affect the active state T_1 and T_2 is shown in fig.7. So it is used for MTSI based grid connected PV system.

Result and discussion

To verify the theoretical analysis in previous section 3kW PV array fed MTSI based transformers grid connected system is simulated. PV panel frame is connected to ground via parasitic capacitance of 220nF and ground resistance of 10.7Ω in P and N point. The minimum dc link voltage necessary to connect PV array to the grid is approximately 350 V (including output filter and the current controller saturation limits).The T-source input voltage and the dc-link capacitor have the value is v_{PN} = 300 V and C_{PN}=2200 μF. The T shape impedance has the following values L_1=L_2 =300 μH, C=360 μF and the switching frequency was fixed as 10kHZ .A shoot through duty cycle(D_s) equal to 0.3335,boost factor (B_f)=3.003 and buck boost factor(B_b)=2.2.in order to have sufficient output voltage to deliver the energy from the PV array to the three phase grid, which was not possible in the trational voltage source inverter. The output LCL filter has the value of L_f=5 mH and C_f =150 μF. In between inverter and grid 2.5kW nonlinear load is connected and grid is designed for 120V RMS voltage. The proposed MTSI based transformer less grid connected PV system is simulated using MATLAB / Simulink.

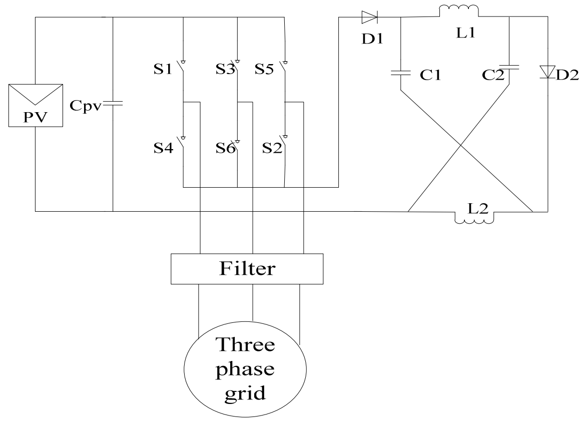


Fig.8 Improved ZSI based grid connected system

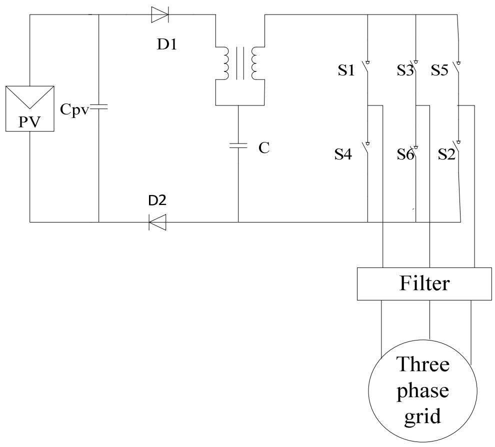


Fig.9 MTSI based grid connected system

Simulation results of Improved ZSI :

Simulation of transformerless IZSI and MTSI PV grid connected systems are in fig 8 and 9 respectively. Fig. 10 Shows the simulation results of Improved ZSI transformer less PV grid connected system with modified space vector pulse width modulation scheme's-Source impedance network parameters are L1=300 μH and C= 1000 μF with a switching frequency of 10kHz is used. It shows more ripples due to high leakage current.Fig.10 (a) and (b) shows the grid current and RMS value (356.78mA) of leakage current. Fig.10 (c) shows common mode voltage of improved ZSI.

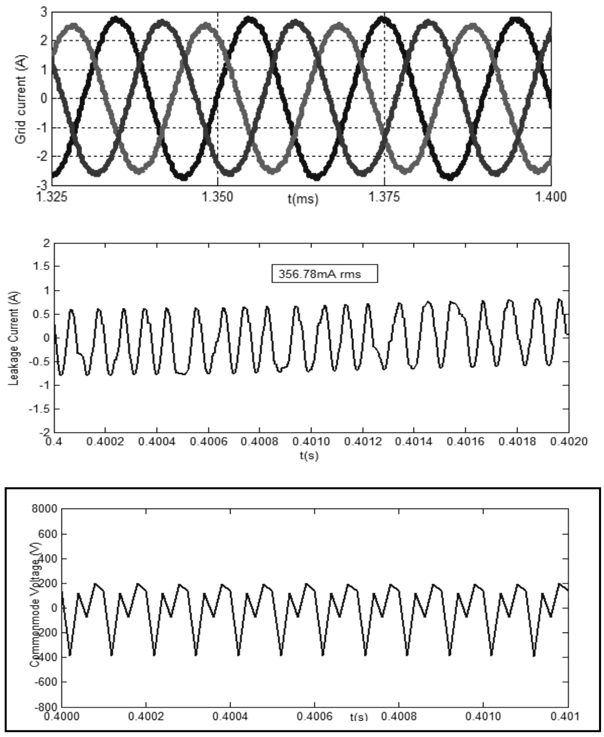


Fig 10. Simulation of Improved ZSI based transformerless grid connected system with MSVPWM. Grid current (b) RMS value of leakage current (c) Common mode voltage (VCM)

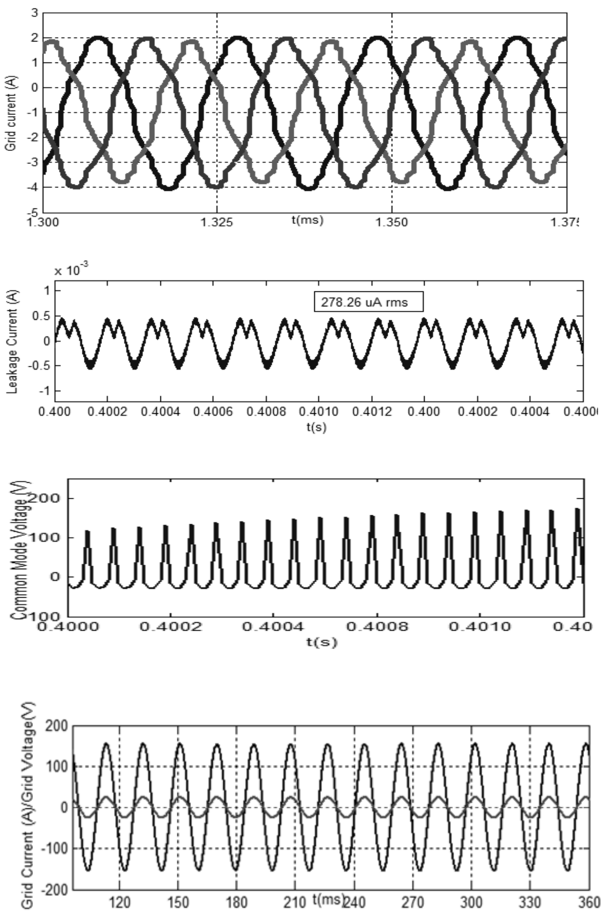


Fig.11 Simulation result of MTSI based transformer less PV grid connected system with MSVPWM. (a) Leakage current (b) RMS Value of Leakage current (c) Common mode voltage and (d) Grid voltage and grid current.

Fig.11 (a),(b) and (c) presents the leakage current and common mode voltage of MTSI based transformer less PV grid connected system. RMS value of leakage current is 278.26 µA. Comparing fig.10 (b)& 11 (b) the RMS value of leakage current in MTSI based tranformerless PV grid connected systems was very less than Improved ZSI based system with same experimental setup and also MTSI based system satisfy the VDE0126 standard for gird connection mode with a threshold value of leakage current is 300mA. MTSI based MSVPWM topology for transformer less PV grid connected system is greatly reduced the leakage current with the reduced reactive component count than Improved ZSI based system.

Simulation results of MTSI :

Fig.12.presents MTSI based transformer less PV grid connected system with nonlinear load. Table 1. Shows the percentage total harmonic distortion (% THD) of MTSI output voltage and load current in grid connected mode condition. Increasing nonlinear load from 500W to 2.5kW %THD value also gets increased within acceptable limits. (IEEE-519). It shows MTSI proved under varying nonlinear load condition also gives satisfactory performance.

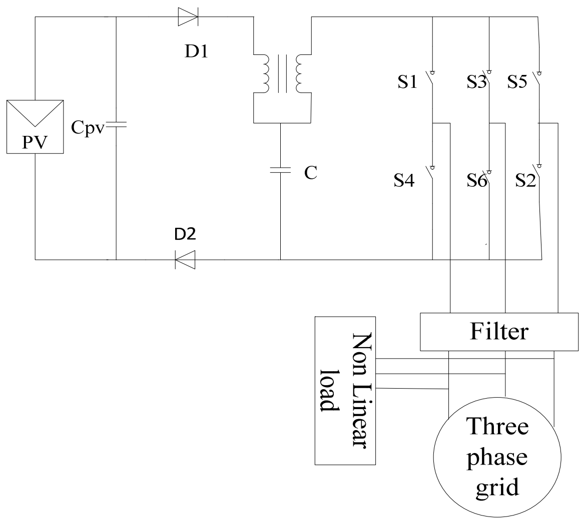


Fig.12 MTSI based transformer less PV grid connected system with nonlinear load.

Experimental results

The field measurement of common mode leakage current of PV system with incorporation MTSI is presented in Fig.13.The common mode voltage and common mode leakage current of the proposed work is shown in Fig 14 and Fig.15.It is evident that leakage current is reduced and within the limit specified by the standard DIN V VDE V 0126-1-1.

Fig.13 Leakage current measurement in the field

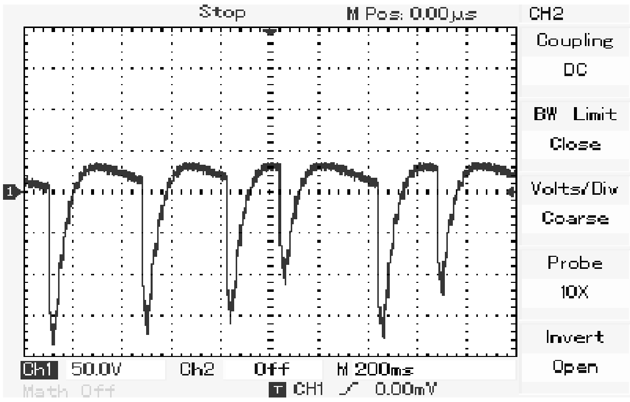


Fig.14 Common mode voltage

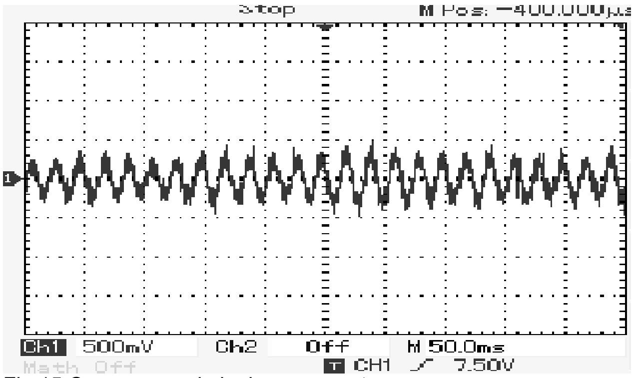
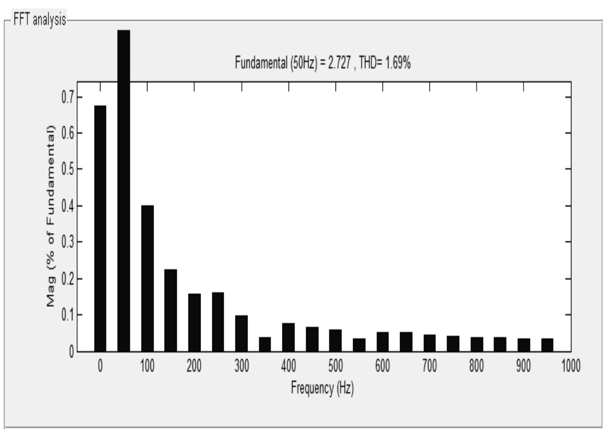


Fig.15 Common mode leakage current

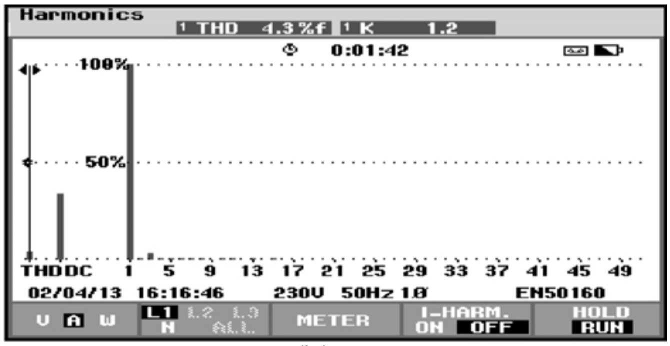
Table:1 THD of the output voltage of the grid connected inverter under Various load condition .

Load (kW)	% THD of grid current With Improved ZSI	% THD of grid current With MTSI
0.2	1.89	1.16
0.4	1.91	1.16
0.6	2.2	1.69
0.8	2.65	2.08
1.0	3.45	2.67

The total harmonic distortion of grid current in improved ZSI mode and MTSI mode based PV system is presented in table 1. It is proved that MTSI has reduced current harmonic than improved ZSI based transformer less grid connected system. THD Spectrum for grid current with non linear load is shown in Fig 16 (a) and (b).Once agin proved the MTSI in grid connected mode with non liner mode the THD value is with in the limit specified by standard IEEE1547.



(a.)



(b.)

Fig. 13 Harmonic spectrum of MTSI based transformerless PV grid connected system with non linear load operation (a)Simulated result.(b) Experimental result.

Conclusion:

The Modified T-Source inverter based transformer less grid connected system with modified space vector modulation scheme has been presented. The common mode voltage and leakage current proposed MTSI in non shoot through and shoot through mode was calculated without affecting the active state of inverter and its compared with the Improved ZSI based system. The comparison results confirm the effectiveness of the proposed inverter with MSVPWM gives reduced leakage current in three phase transformer less PV grid connected systems .It is tested under nonlinear load condition it gives satisfactory performance specified by the standards.

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