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Analysis and Design of Solar Photo Voltaic Grid Connected Inverter

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Abstract

This paper presents common mode voltage analysis of single phase grid connected photovoltaic inverter. Many researchers proposed different grid tie inverters for applications like domestic powering, street lighting, water pumping, cooling and heating applications, however traditional grid tie PV inverter uses either a line frequency or a high frequency transformer between the inverter and grid but losses will increase in the network leading to reduced efficiency of the system. In order to increase the efficiency, with reduced size and cost of the system, the effective solution is to remove the isolation transformer. But common mode (CM) ground leakage current due to parasitic capacitance between the PV panels and the ground making the system unreliable. The common mode current reduces the efficiency of power conversion stage, affects the quality of grid current, deteriorate the electric magnetic compatibility and give rise to the safety threats. In order to eliminate the common mode leakage current in Transformerless PV systm two control algorithms of multi-carrier pwm are implemented and compared for performance analysis.The shoot-through issue that is encountered by traditional voltage source inverter is analyzed for enhanced system reliability. These control algorithms are compared for common mode voltage and THD comparisons. The proposed system is designed using MATLAB/SIMULINK software for analysis.

Keywords*: common mode leakage current, transformerless grid connected PV inverter, SPWM, PD*

1. Introduction

Grid tie photovoltaic (PV) systems, particularly low-power single-phase systems up to 5 kW, are becoming more important worldwide. They are usually private systems where the owner tries to get the maximum system profitability. Issues such as reliability, high efficiency, small size and weight, and low price are of great importance to the conversion stage of the PV system [1]–[3]. Quite often, these grid-connected PV systems include a line transformer in the power-conversion stage, which guarantees galvanic isolation between the grid and the PV system, thus providing personal protection. Furthermore, it strongly reduces the leakage currents between the PV system and the ground, ensures that no continuous current is injected into the grid, and can be used to increase the inverter output voltage level [1],[2],[4]. The line transformer makes possible the use of a full-bridge inverter with unipolar pulse width modulation (PWM). This inverter is simple and it requires only four insulated gate bipolar transistors (IGBTs) and has a good trade-off between efficiency, complexity and price [5].

Due to its low frequency, the line transformer is large, heavy and expensive. Technological evolution has made possible the implementation, within the inverters, of both ground-fault detection systems and solutions to avoid injecting dc current into the grid. The transformer can then be eliminated without impacting system characteristics related to personal safety and grid integration [1],[4],[6]–[8]. In addition, the use of a string of PV modules allows maximum power point (MPP) voltages large enough to avoid boosting voltages in the conversion stage. This conversion stage can then consist of a simple buck inverter, with no need of a transformer or boost dc–dc converter, and it is simpler and more efficient. But if no boost dc–dc converter is used, the power fluctuation causes a voltage ripple in the PV side at double the line frequency. This in turn causes a small reduction in the average power generated by the PV arrays due to the variations around the MPP. In order to limit the reduction, a larger input capacitor must be used. Typical values of 2 mF for this capacitor limit the reduction in the MPPT efficiency to 1% in a 5-KW PV system [8]. However, when no transformer is used, a galvanic connection between the grid and the PV array exists. Dangerous leakage currents

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(common-mode currents) can flow through the large stray capacitance between the PV array and the ground if the inverter generates a varying common-mode voltage [1]-[4].

Recently, several transformerless inverter topologies have been presented that use super junction MOSFETs devices as main switches to avoid the fixed voltage-drop and the tail-current induced turn-off losses of IGBTs to achieve ultra high efficiency. However, this topology has high conduction losses due to the fact that the current must conduct through three switches in series during the active phase. Another disadvantage of the H5 is that the line-frequency switches S1 and S2 cannot utilize MOSFET devices because of the MOSFET body diode's slow reverse recovery. The slow reverse recovery of the MOSFET body diode can induce large turn-on losses, has a higher possibility of damage to the devices and leads to EMI problems. Shoot-through issues associated with traditional full bridge PWM inverters remain in the H5 topology due to the fact that the three active switches are series-connected to the dc bus Replacing the switch S5 of the H5 inverter with two split switches S5 and S6 into two phase legs and adding two freewheeling diodes D5 and D6 for freewheeling current flows, the H6 topology was proposed [9]-[10].

The H6 inverter can be implemented using MOSFETs for the line frequency switching devices, eliminating the use of less efficient IGBTs. The fixed voltage conduction losses of the IGBTs used in the H5 inverter are avoided in the H6 inverter topology improving efficiency; however, there are higher conduction losses due to the three series-connected switches in the current path during active phases. The shoot-through issues due to three active switches series connected to the dc-bus still remain in the H6 topology. Another disadvantage to the H6 inverter is that when the inverter output voltage and current has a phase shift the MOSFET body diodes may be activated. This can cause body diode reverse-recovery issues and decrease the reliability of the system. The adjustment to improve the system reliability comes at the cost of high zero-crossing distortion for the output grid current one key issue for a high efficiency and reliability transformerless PV inverter is that in order to achieve high efficiency over a wide load range it is necessary to utilize MOSFETs for all switching devices. Another key issue is that the inverter should not have any shoot-through issues for higher reliability [11]-[13]. The Figure 1 shows the improvements to traditional systems for common mode voltage analysis.

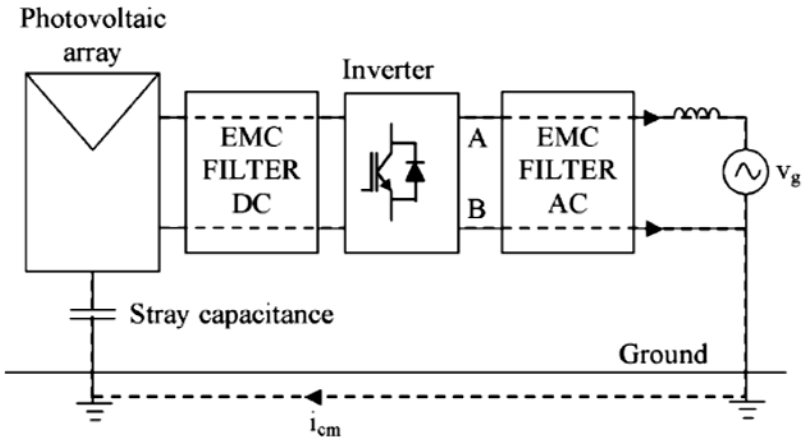

Figure 1. Common-mode currents in a transformerless conversion stage

In order to address these two key issues, a new inverter topology is proposed for single-phase transformerless PV grid-connected systems in this paper. The proposed converter utilizes two split ac-coupled inductors that operate separately for positive and negative half grid cycles. This eliminates the shoot-through issue that is encountered by traditional voltage source inverters, leading to enhanced system reliability. Dead time is not required at both the high-frequency pulse width modulation switching commutation and the grid zero crossing instants, improving the quality of the output ac-current and increasing the converter efficiency.

This paper is organized as section I is about the literature survey on transformerless PV inverter, sections II is presented about proposed topology with Sine PWM its principle of

operation, section III is about common voltage analysis of proposed system, section IV matlab implementation of the proposed system with sine PWM and Phase Disposition technique. Comparison of two techniques for THD of output voltages with reduced leakage current is shown.

2. The Proposed Topology and Operational Analysis

The proposed topology is shown in Figure 2. Circuit diagram of the proposed transformerless PV inverter, which is composed of six MOSFETs switches (S1–S6), six diodes (D1–D6), and two split ac-coupled inductors *L*1 and *L*2. The diodesD1–D4 performs voltage clamping functions for active switches S1–S4. The ac-side switch pairs are composed of S5, D5 and S6, D6, respectively, which provide unidirectional current flow branches during the freewheeling phases decoupling the grid from the PV array and minimizing the CM leakage current.

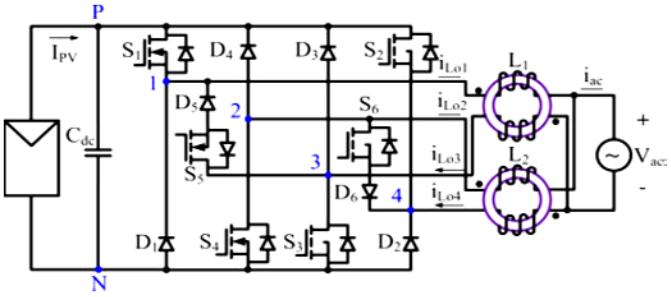

Figure 2. Proposed high efficiency and reliability PV transform less inverter topology.

Compared to the HERIC topology the proposed inverter topology divides the ac side into two independent units for positive and negative half cycle. In addition to the high efficiency and low leakage current features, the proposed transformerless inverter avoids shoot-through enhancing the reliability of the inverter. The inherent structure of the proposed inverter does not lead itself to the reverse recovery issues for the main power switches and as such super junction MOSFETs can be utilized without any reliability or efficiency Penalties.

Figure 3 illustrates the PWM scheme for the proposed inverter. When the reference signal *V*control is higher than zero, MOSFETs S1 and S3 are switched simultaneously in the PWM mode and S5 is kept on as a polarity selection switch in the half grid cycle; the gating signals G2, G4, and G6 are low and S2, S4, and S6 are inactive. Similarly, if the reference signal –*V*control is higher than zero, MOSFETs S2 and S4 are switched simultaneously in the PWM mode and S6 is on as a polarity selection switch in the grid cycle; the gating signals G1, G3, and G5 are low and S1, S3, and S5 are inactive.

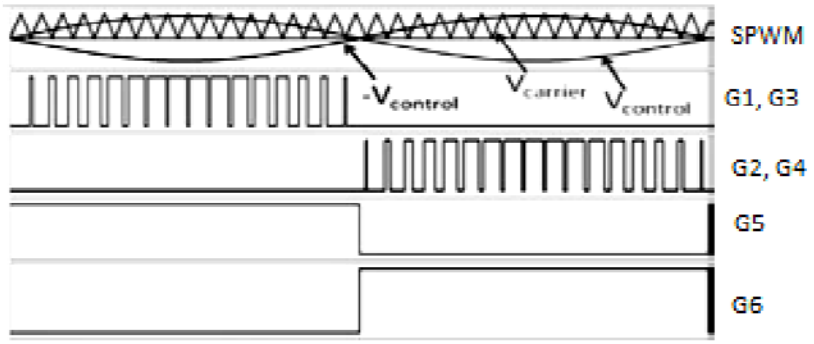

Figure 3. Phase disposition PWM signal used to control the system

Table 1. Switching states and respective common mode voltages

S_1	S_2	S_3	S_4	S_5	S_6	V_{cm}	Sequence
pwm	off	off	pwm	on	off	$U_{dc}/2$	positive
off	off	off	off	off	off	$U_{dc}/2$	
off	pwm	pwm	off	of	on	$U_{dc}/2$	negative
off	off	off	off	off	off	$U_{dc}/2$	

Figure 4 shows the four operation stages of the proposed inverter within one grid cycle. In the positive half-line grid cycle, the high-frequency switches S1 and S3 are modulated by the sinusoidal reference signal $V_{control}$ while S5 remains turned ON.

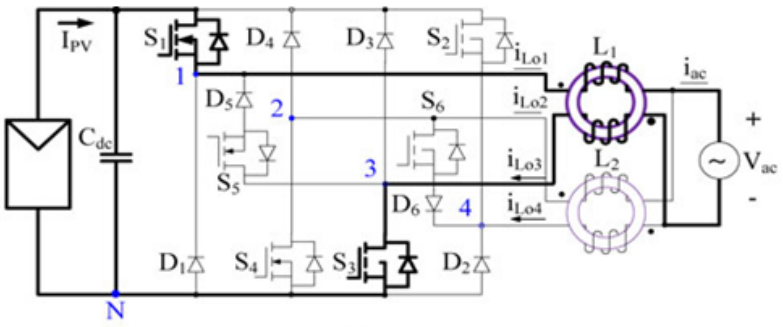

Figure 4. Active stage of positive half-line cycle

When S1 and S3 are ON, diode D5 in Figure 5 is reverse-biased, the inductor currents of *i*Lo1 and *i*Lo3 are equally charged, and energy is transferred from the dc source to the grid.

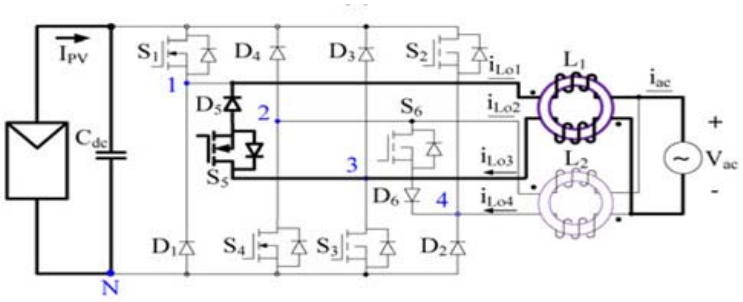

Figure 5. Freewheeling stage of positive half-line cycle

When S1 and S3 are deactivated, the switch S5 and diode D5 in Figure 6 provide the inductor current *iL*1 and *iL*3 a freewheeling path decoupling the PV panel from the grid to avoid the CM leakage current. Coupled-inductor *L*2 is inactive in the positive half-line grid cycle.

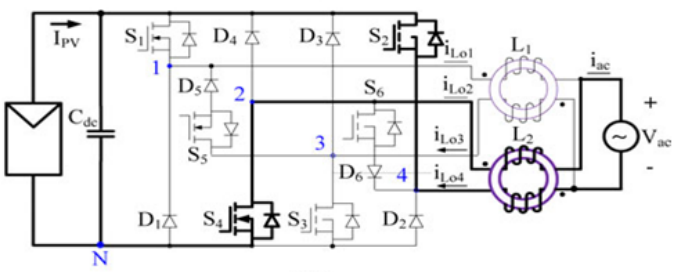

Figure 6. Active stage of negative half-line cycle

Similarly, in the negative half cycle, S2 and S4 in Figure 7 are switched at high frequency and S6 remains ON. Freewheeling occurs through S6 and D6. When S2 and S4 are ON, diode D6 is reverse-biased, the inductor currents of *i*Lo2 and *i*Lo4 are equally charged, and energy is transferred from the dc source to the grid; when S2 and S4 are deactivated, the switch S6 and diode D6 provide the inductor current *iL*2 and *iL*4 a freewheeling path decoupling the PV panel from the grid to avoid the CM leakage current.

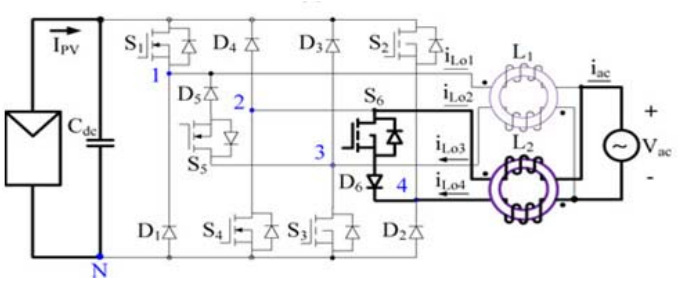

Figure 7. Freewheeling stage of negative half-line cycle

3. Ground Loop Leakage Current Analysis for the Proposed Transformerless Inverter

A galvanic connection between the ground of the grid and the PV array exists in transformerless grid-connected PV systems. Large ground leakage currents may appear due to the high stray capacitance between the PV array and the ground. In order to analyze the ground loop leakage current, Figure 8 shows a model with the phase output points 1, 2, 3, and 4 modeled as controlled voltage sources connected to the negative terminal of the dc bus (N point).

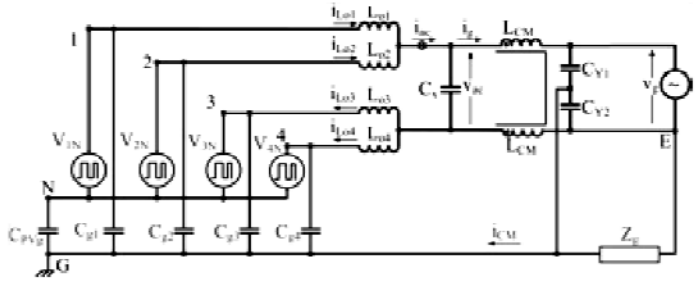

Figure 8. Simplified CM leakage current analysis model for positive half-line cycle

The value of the stray capacitances *Cg*1*, Cg*2*, Cg*3, and *Cg*4 of MOSFETs is very low compared with that of *C*PVg, therefore the influence of these capacitors on the leakage current can be neglected. It is also noticed that the DM capacitor *Cx* does not affect the CM leakage current. Moreover, during the positive half-line cycle, switches S_2, S_4, and S_6 are kept deactivated; hence the controlled voltage sources V_{2N} and V_{4N} are equal to zero and can be removed. Consequently, a simplified CM leakage current model for the positive half-line cycle is derived as shown in Figure 8.

4. Matlab Verification of the Proposed Circuit

The Figure 9 is the Matlab design of proposed system with unipolar PWM with the switching frequency of 20KHz. Sine PWM is used to generate the control signals to convert DC of supply into AC supply. The subsystem of Solar PV system is shown in Figure 10.

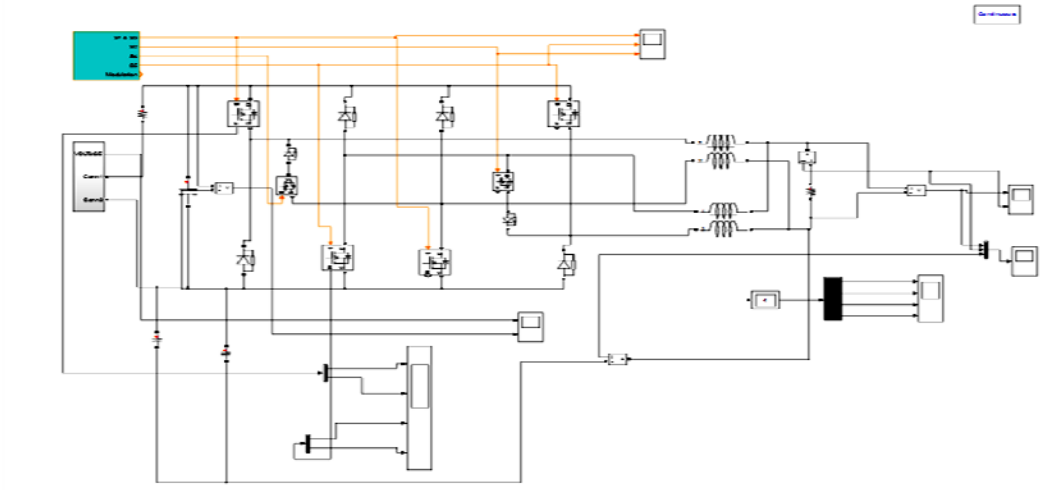

Figure 9. Proposed circuit in Matlab

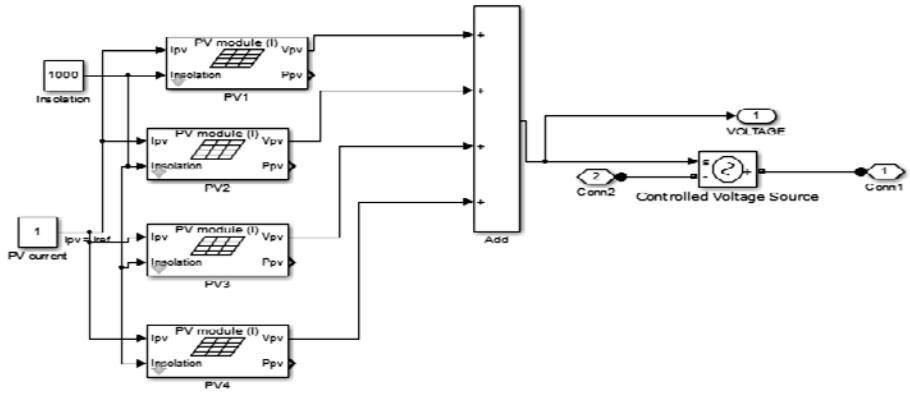

Figure 10. Solar pv system designed in Matlab

Phase of Disposition is the one multi-carrier pwm applied to the proposed system for common mode analysis. Multiple carriers were chosen based on the principle of POD pwm technique is shown in Figure 11.

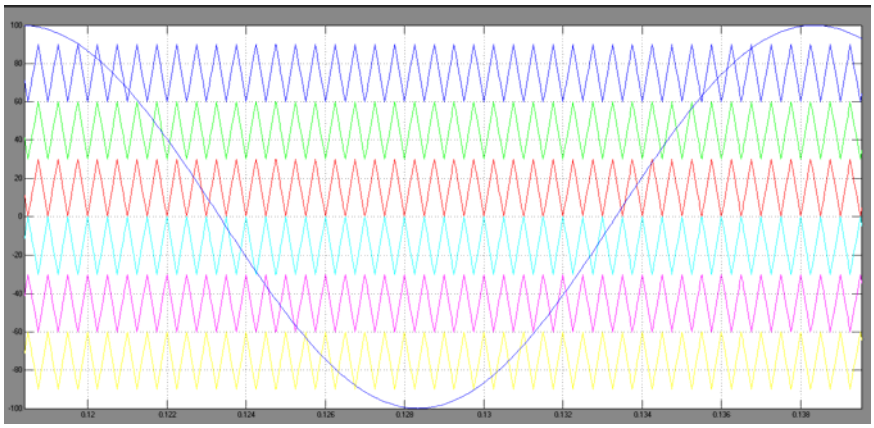

Figure 11. POD pwm applied to proposed system

The inverter output voltage and current waveform is shown in Figure 12 with output voltage of 230V, 50Hz and 4 amps of current is obtained as AC grid tie output. The green waveform is shown in figure represents the leakage currents due to common mode voltages.

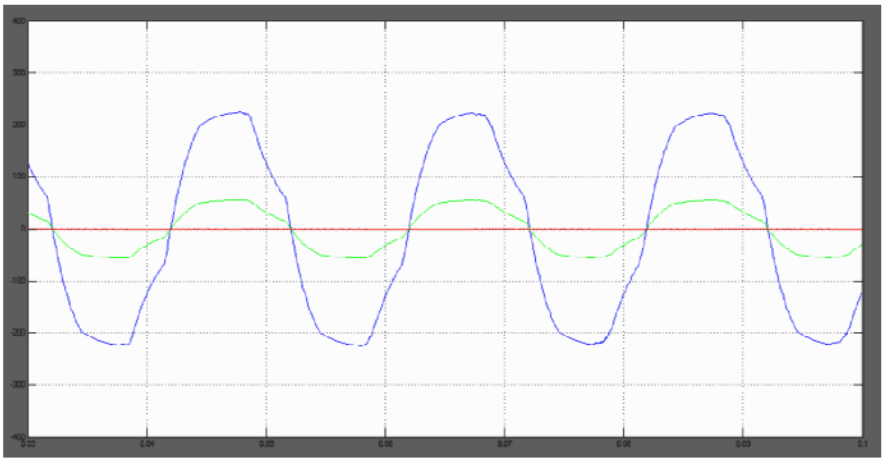

Figure 12. Grid voltage and current

As shown in the proposed circuit the output of inverter is not directly connected to grid, two inductive filters are employed for positive half and negative half cycle of the output independently. The waveforms represent the currents through the inductors for positive and negative half of full cycle. Figure 13 shows the closer image of the leakage current due to the common mode voltage. The Figure 14 shows the individual currents that flow through the filter inductor during both half cycles.

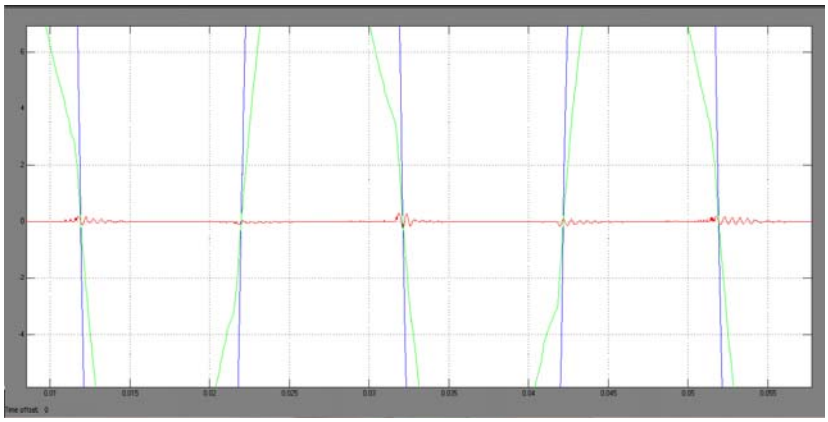

Figure 13. Common mode leakage current with POD PWM

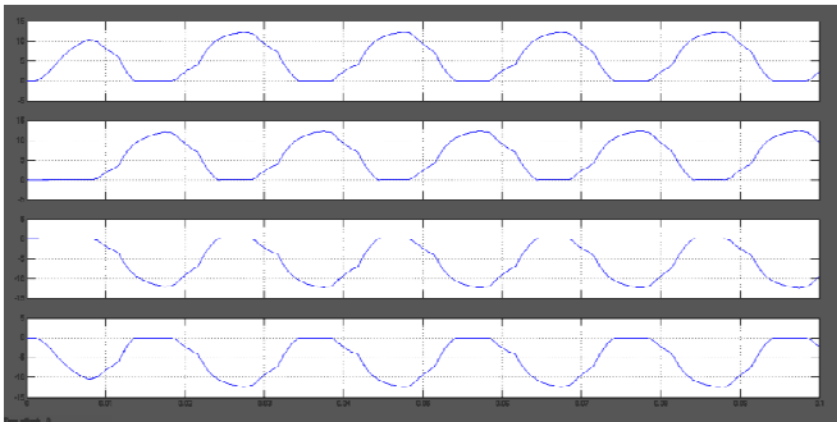

Figure 14. Inductor currents of *i*Lo1, *i*Lo2, *i*Lo3 and *i*Lo4

The Figure 15 shows the total Harmonic distortion of output voltage tied to grid while using sine PWM as the pulse generator, it is found that the THD is about 14.60%.

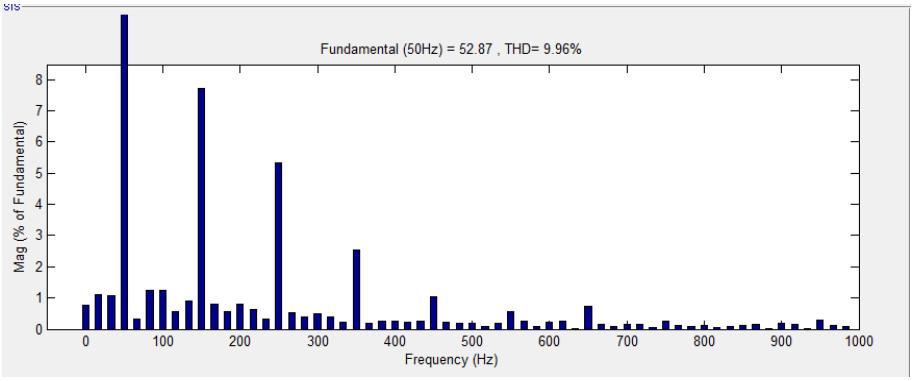

Figure 15. THD of output voltage using POD PWM technique

Phase opposition is the one of the efficient technique among the PD, POD, APOD, Figure 16 shows the PD technique implemented by using Matlab for generating gate signals it is evident from Figure 17 that the leakage current due to common mode voltage is became nearly to zero and the total harmonic distortion is reduced to 9.86%.

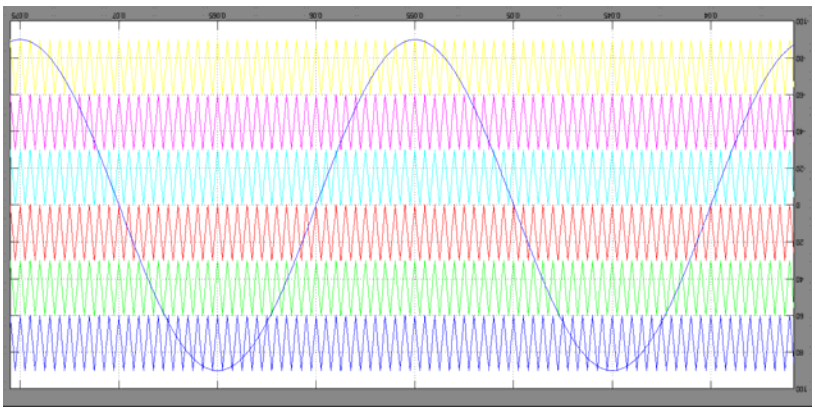

Figure 16. Phase Disposition modulation technique applied to proposed system

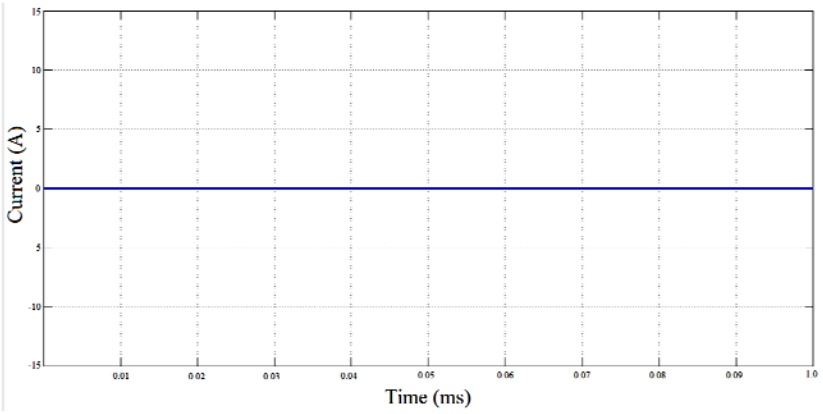

Figure 17. Reduced Leakage currents when applying PD technique

The Figure 6 is the gate pulse generation for the proposed converter for 20KHZ operating frequency of converter. The figure 11 is the grid voltages and current at pcc. The Figure 14 gives grid voltage, inductor currents of *i*Lo1 and *i*Lo2. The main of this project is reducing common mode currents is presented in Figure 17. The Figure 18 shows the THD of output voltage is about 2.22% shows that power quality is up to the mark. According to IEEE standard 5% of THD is acceptable limit.

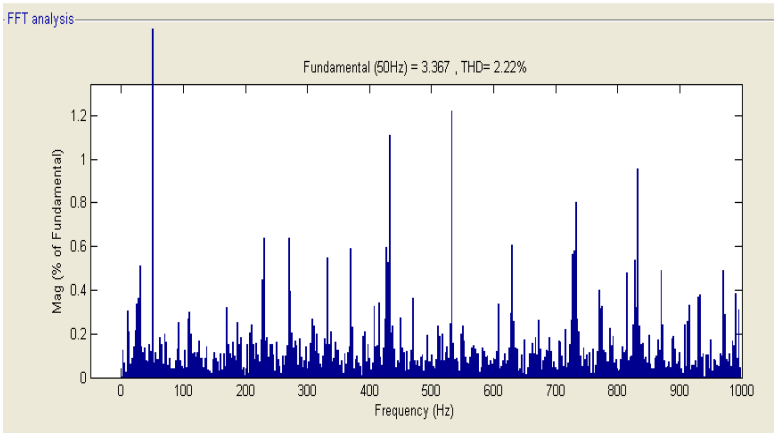

Figure 18. FFT analysis using PD technique

5. Conclusion

A high reliability and efficiency inverter for transformerless solar PV grid-connected systems is presented in this paper using Matlab/Simulink model design. The leakage current present due to the effect of common mode voltage with POD PWM and PD PWM are applied on the proposed converter performance analysis interms of THD. It is observed from FFT analysis of POD and PD pwm techniques that PD has very low thd and also the characteristics of the proposed transformerless inverter shows the reduced shoot-through issue leads to greatly enhanced reliability, low ac output current distortion is achieved because a high dead time is not needed at PWM switching commutation instants in the case of PD technique. It is shown that the proposed transformerless PV grid tie inverter is efficient when using PD as control technique for controlling the switching operation with overall improved efficiency.

The asymmetry of the switch arrangements in less usage of the number of high frequency switches in order to reduce the losses and increase the efficiency of proposed system will be a good option.

Appendix

Parameters	Specifications
Input voltage	440V DC
Grid voltage/ Frequency	230V/50Hz
Rated Power	1000W
Switching Frequency	20KHz
Dc bus capacitor	470µF
Filter capacitor	4.7µF
Filter Inductors	2mH
Parasitic capacitors	750nF

References

[1] SB. Kjaer, JK. Pedersen, F. Blaabjerg. A review of single-phase grid-connected inverters for photovoltaic modules. *IEEE Trans. Ind. Appl.* 2005; 41(5): 1292–1306.
[2] R. Gonzalez, E. Gubia, J. Lopez, L. Marroyo. Transformerless single phase multilevel-based photovoltaic inverter. *IEEE Trans. Ind. Electron*. 2008; 55(7): 2694–2702.
[3] SV. Araujo, P. Zacharias, R. Mallwitz. Highly efficient single-phase transformer-less inverters for grid-connected photovoltaic systems. *IEEE Trans. Power Electron*. 2010; 57(9): 3118–3128.
[4] W. Yu, JS. Lai, H. Qian, C. Hutchens. High-efficiency MOSFET inverter with H6-type configuration for photovoltaic non-isolated AC-module applications. *IEEE Trans. Power Electron*. 2011; 56(4): 1253–1260.
[5] T. Kerekes, R. Teodorescu, P. Rodriguez, G. Vazquez, E. Aldabas. A new high-efficiency single-phase transformerless PV inverter topology. *IEEE Trans. Ind. Electron*. 2011; 58(1): 184–191.
[6] B. Yang, W. Li, Y. Zhao, X. He. Design and analysis of a grid connected photovoltaic power system. *IEEE Trans. Power Electron*. 2010; 25(4): 992–1000.
[7] H. Xiao, S. Xie, Y. Chen, R. Huang. An optimized transformerless photovoltaic grid-connected inverter. *IEEE Trans. Ind. Electron*. 2011; 58(5): 1887–1895.
[8] B. Yang, W. Li, Y. Gu, W. Cui, X. He. Improved transformerless inverter with common-mode leakage current elimination for photovoltaic grid-connected power system. *IEEE Trans. Power Electron*. 2012; 27(2): 752–762.
[9] M. Calais, VG. Agelidis. Multilevel converters for single-phase grid connected photovoltaic systems: an overview. Proc. IEEE Int. Symp. Ind. Electron. 1998; 1: 224–229.
[10] M. Calais, JMA. Myrzik, VG. Agelidis. Inverters for single phase grid connected photovoltaic systems—Overview and prospects. Proc. 17th Eur. Photovoltaic Solar Energy Conf., Munich, Germany. 22–26 Oct. 2001: 437–440.
[11] IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems. IEEE Std. 1547. 2003.
[12] V. Verband der Elektrotechnik. Elektronik und Informationstechnik (VDE). Std. V 0126-1-1, Deutsches Institut für Normung. 2006.
[13] WN. Mohan, T. Undeland, WP. Robbins. *Power Electronics: Converters, Applications, and Design*. New York. Wiley. 2003.