

Grid Connected, Transformer less Single phase Inverter Topologies for Photovoltaic systems

Selvamathi R, V Indragandhi, AshokKumar L, Ramani Kannan

Abstract: In order to provide safety to users, the design of a majority of the photovoltaic (PV) systems is made with galvanic isolation and with transformer. During conversion stage's overall frequency is decreased because the transformer is expensive, heavy and bulky. The general efficiency of PV inverters with transformers ranges approximately from 92% to 94%. Therefore, a more effective, inexpensive, lighter and smaller PV system without transformer is introduced for managing such issues. For inverters without transformer, several kinds of configurations, such as dual parallel buck inverter, oH5, HERIC, H5, H6, etc., are available. However, several disadvantages, such as MOSFET reverse recovery issues, dead time necessities at the grid voltage's zero crossing instances (for the avoidance of grid shoot-through by faults), shoot-through by switch issues, and high conduction losses, are associated with such configurations. Two problems are associated with the proposed inverter without transformer. The first problem is that in order to attain a higher efficiency, super junction MOSFETs (CoolMOS) have to be utilized for all switching devices. The second problem is that no shoot-through problems must be experienced by the inverter's configuration for attaining a higher reliability. A detailed analysis of the entire above transformerless inverter with simulation results obtained from Simulink is presented in this paper.

Index Terms: Grid Connected System, Phovoltaics, Reverse Recovery, Shoot-Through, Transformerless Inverter (TLI).

I. INTRODUCTION

Solar photovoltaic (PV) systems are considered as one of the most promising distributed energy resources (DERs) and the grid integration of such PV systems is performed through inverters. Over last few years, there have been significant development on inverter technologies and the main reasons behind all these development are the improvements in the efficiency and the reductions in costs. The grid integration of PV units becomes more expensive when transformers are used as the costs associated with transformers are high. For this reason, it is important to consider transformerless inverters (TLIs) for the PV based systems synchronized with grid. The existing literature about TLIs include different configurations such as dual-parallel back inverters, H5

inverters, optimized H5 (oH5) inverters, H6 inverters, high efficient and reliable inverter Concept (HERIC) [A1]. The IGBTs' fixed voltage conduction losses are utilized in the H5 inverter to enhance the efficiency, these fixed voltage conduction losses are not utilized in the topology of the H6 inverter [1–2]. Nevertheless, the three switches are serially connected in the present path cause greater losses of conduction during the active stages. The H6 topology still contains the shoot-through problems due to the three DC-bus connected switches in a serial connection [3–4]. The diodes of the MOSFET body may be activated when there is change in phase of inverter current and output, eventually proving to be H6 inverter's yet another disadvantage. This may lead to a reduction in the system's reliability and the reversal of recovery issues by body diode. Therefore, a highly efficient and reliable topology is proposed for inverter without transformer for solving these issues.[5–6]. The presence of full bridge inverter topology with Common Mode (CM) currents and varying Pulse Width Modulation (PWM) methods are observed from the review of literature. The new topology, function with any power factor, is highly efficient, and does not produce mode voltage[8–9]. Ground current and a difference in the ground currents of the full bridge's unipolar and bipolar modulation strategies were examined and it was proposed that, the full bridge inverter be substituted with a neutral point clamped topology[10–12].

Several factors like, leakage current, CM voltage, output current, and output voltage are considered in the discussion of single phase TLI topologies tied to grid, such as H5, and H6 and HERIC topologies. The oH5 topology is proposed due to the combined advantages of both unipolar modulation and bipolar modulation in the topology. The input voltage is improved to the voltage of the freewheeling path for avoiding the oH5 topologies CM voltage [13–15]. To attain a high efficiency, MOSFET and IGBT devices are utilized and the ground leakage current issue is solved by a commercialized unipolar inverter H5 topology. High conduction losses are possessed by the H5 topology, because the current is conducted through three serially connected switches during the active stage. The MOSFET devices cannot be utilized by the line frequency switches S1 and S2, due to its slow reverse recovery diode, which constitutes another disadvantage of the H5 topology. Large losses can be induced by the EMI problems, they are potentially caused by a higher probability of damage to devices, due to the slow reverse recovery diode. Since all active power switches are attached serially to the DC bus, the topology of H5 possesses the shoot-through problems that are related with conventional PWM inverters with full-bridge structure.

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The H6 topology was proposed in which two split switches, S5 and S6, replaced the H5 inverter's S5 switch in the form of two phase legs. The utilization of less effective IGBTs can be eliminated through the implementation of the H6 inverter by using MOSFETs as switching devices. In order to enhance the efficiency, the IGBT's fixed voltage operating losses used in the H5 topology are not used in the H6 topology [16–17]. Nevertheless, the three switches serially connected in the path of current cause higher operating losses during the active stages. The H6 topology still possesses the shoot-through problems, because of the three serially connected active switches. When there is change in phase of output current and inverter voltage, activation of MOSFET body diodes may occur, thereby constituting one more difficulty to the H6 inverter. This scenario can cause problems in the reverse recovery of body diode and can reduce the reliability of the system[18].

Dual paralleled buck converter is another highly efficient MOSFET inverter topology without transformer. The dual-boost and bridgeless circuit of Power Factor Correction (PFC) is used for the inverse derivation of the dual parallel buck converter. Due to the presence of only two active switches which are serially connected with the path of current throughout the active stages, the issue of high operating losses is eliminated in the inverter topologies of H5 and H6 by the paralleled dual buck inverter. The primary issue of this topology is that its reliability is decreased due to the possibility of a grid short circuit caused by the direct connection of the two dynamic switches (S3 and S4) with the grid. A dead-time of 500 μ s must be added at the zero crossing instants between S3 and S4 (line-frequency switches) for preventing the shoot-through of the grid.

A maximum efficiency of 96% is rendered by Sunny Boy 2100TL series inverters without transformers that employ SMA solar technology AG, which has patented the H5 configuration. A maximum efficiency of 97.6% is given by the solar edge with same H5 configuration single phase inverters of SE2200 – SE6000 series. A maximum efficiency of 97.8% is rendered by the HERIC configuration, which is patented by Sunways and used in their NT series inverters. A maximum efficiency of 97.8% is given for 6 kW loads and a maximum efficiency of 97.9% is given for 8 kW loads is given by the Danfoss Company's TLX series of HERIC configuration inverters.

In the H6 inverter topology, for efficiency improvement, IGBT's are not used due to fixed voltage conduction losses which are been used in H5 Inverter. In H6 topology, because of three serially connected active switches to the DC bus, shoot through issues are remaining same. One more drawback of H6 inverter is, MOSFET body diodes being activated, when the inverter output voltage and current has a change in phase. Dual-parallel-buck topology's key problem is reduction of reliability, because of the directly connected grid using two active switches, which may source to short circuit problem in grid. The above issues are shorted out by designing a new transformer-less inverter.

This research article organized as follows: Section 2 deal about proposed topology and its operation. In section 3 the existing TLI and its operations are presented. The

proposed topology waveforms are given in section 4 and section 5 concludes our paper.

II. OVERVIEW OF DIFFERENT EXISTING TLIS

This section aims to discuss an summary of the most commonly used topologies for grid-connected PV systems. The following subsections provide an overview of these topologies.

A. Full-bridge with the unipolar modulation

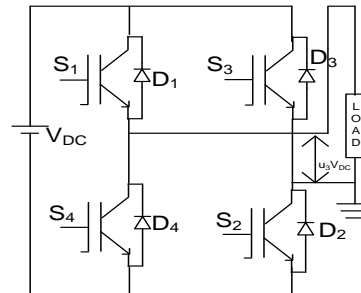


Fig 1. (a) Full-bridge topology

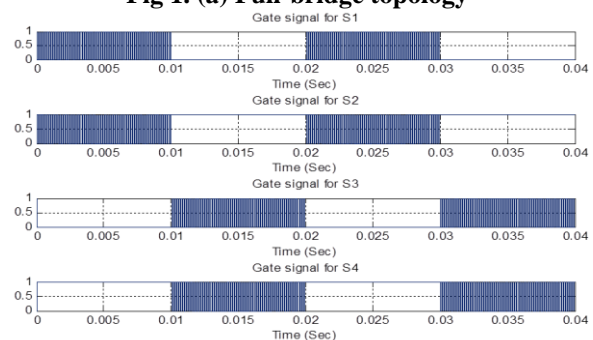


Fig 1.(b) Unipolar pulse patterns for the full-bridge inverter

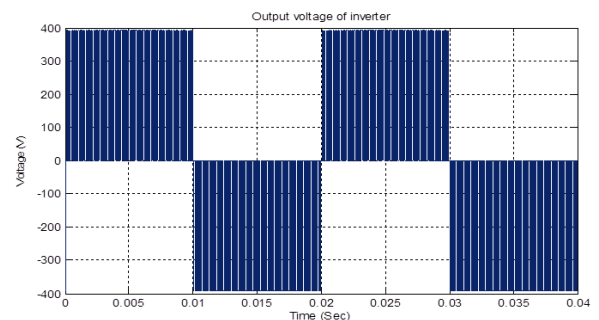


Fig 1. (c) Output voltage - PWM Inverter

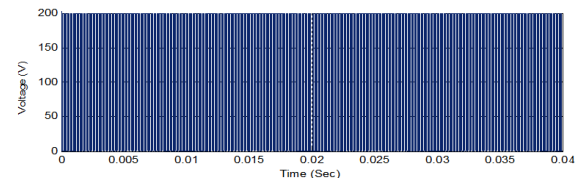


Fig 1 (d) CM voltage -PWM Inverter

The H-bridge topology is shown in Fig 1(a) while the unipolar pulse patterns are shown in Fig 1 (b) . Fig 1 (c) shows the output voltage of the full-bridge inverter with the unipolar PWM from where it can be seen that there are three-levels (+Vdc, 0, -Vdc) in the output voltage.

This three-level output voltage is produced by a unipolar (three-level) modulation scheme where the voltage across the inductor varies by V_{dc} in every switching transition. Therefore, the unipolar PWM scheme reduces losses, sizes of filters, ripple currents, and changes in the voltage (i.e., dv/dt) in both inductors and switches. The CM voltage of the full-bridge inverter with the unipolar PWM is shown in Fig 1(d). This CM voltage is produced by stray capacitances which are energized by the voltage oscillating with the switching frequency. A few amperes of unsafe leakage current is produced by such a high frequency CM voltage. Therefore, the unipolar PWM is not appropriate for the full-bridge topology without transformers.

B. Full-bridge with the bipolar modulation

The bipolar modulation requires only a single sinewave which is more suitable for the full-bridge inverter in transformerless grid-connected PV applications compared to the unipolar modulation technique. The inverter output voltage switches between either positive (+ V_{dc}) or negative (- V_{dc}) DC voltages.

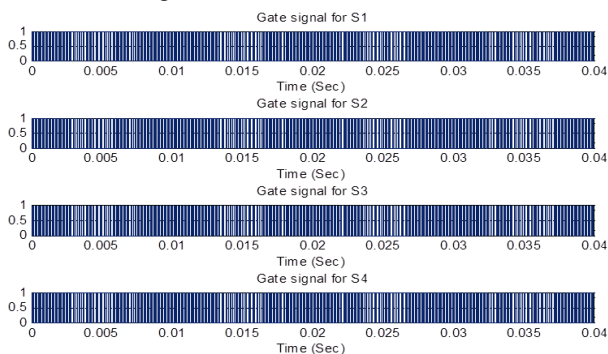


Fig 2(a) Bipolar pulse patterns for the full-bridge inverter.

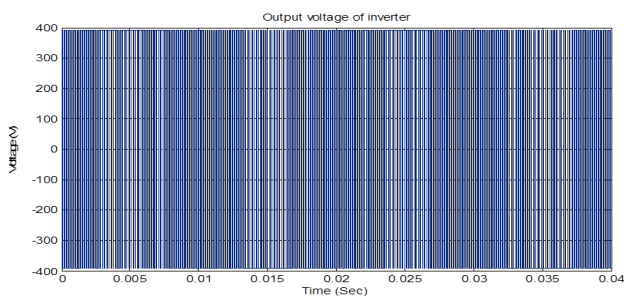


Fig 2(b) Output voltage of the bipolar PWM Inverter

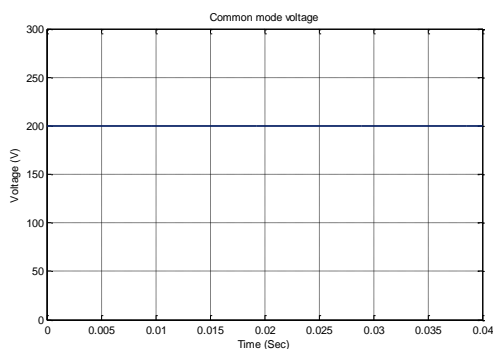


Fig 2(c) CM voltage of the bipolar PWM inverter

C. Other Topologies

The bipolar pulse patterns for the full-bridge inverter are shown in Fig 2(a). Fig 2 (b) shows the output voltage of the

full-bridge inverter with the bipolar PWM from where it can be seen that there are two-levels (+ V_{dc} and - V_{dc}) in the output voltage. . This two-level output voltage is produced by a bipolar (two-level) modulation scheme where the voltage across the inductor varies by $2V_{dc}$ in every switching transition. There are high switching losses and large ripples in the current through inductors which decrease overall efficiency of this inverter and make the modulation scheme ineffective. However, the CM voltage as shown in Fig 2 (c) significantly reduces the leakage current while comparing the with the unipolar PWM scheme.

The topology of the H5 inverter a supplementary switch is added at the input DC-side of the full-bridge structure in order to modify it into the H5 topology. When the PV system is disconnected from the utility through the disconnection of switch in the inverter’s DC side, the H5 topology is also known as the DC decoupling configuration. The full-bridge topology is modified to the HERIC topology where this modification is done through two additional switches on the AC-side. During the first half-cycle of the grid voltage, each diagonal switch is activated at the switching frequency. In the HERIC topology, PV is disconnected from the grid through the short-circuit on the AC-side. In the H6 topology, the traditional full-bridge inverter includes a pair of additional diodes and switches. The additional switches are employed in order to disconnect the PV unit from the grid. The topology of the oH5 is quite similar to that of the H6 where the voltage of the drifting path is fastened to the half of the input voltage. It can be summarized that all topologies except the unipolar modulation are appropriate for utilization in transformerless grid-connected PV systems.

III. PROPOSED TLI TOPOLOGY FOR GRID-CONNECTED PV SYSTEMS

The circuit diagram of the proposed topology is shown in Fig 3. from where it can be seen that the inverter is made up of a pair of split inductors ($L1$ and $L2$), six diodes ($D1$ to $D6$), and six MOSFET switches ($S1$ - $S6$). The tasks of voltage clamping for the active power switches $S1$ to $S4$ are executed by the diodes $D1$ - $D4$. During the freewheeling stages, unidirectional current flow branches are provided by switch pairs on the AC-side where these pairs are $S5, D5$ and $S6, D6$. The CM leakage current is minimized and the decoupling of the grid from the PV array is done through this phase.

In this circuit, the AC-side is separated into a pair of autonomous units for negative half cycles (NHCs) and positive half cycles (PHCs) while comparing with the HERIC topology. Apart from high efficiency and low leakage current characteristics, the shoot-through is prevented by the proposed TLI and the proposed topology exhibits improved reliability. The super junction-type MOSFETs are used without any penalty related to the reliability or efficiency as the proposed inverter’s underlying structure does not lead on its own primary power switches to the reverse recovery issues. The operational features of the proposed TLI along with the analysis of the leakage current are discussed in the following subsection.



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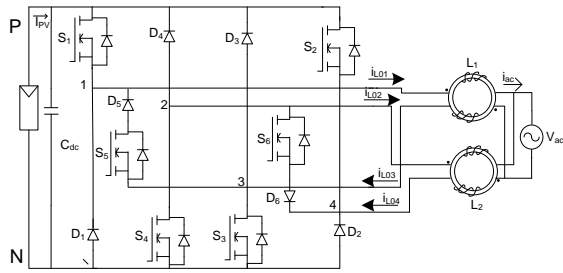


Fig 3. Proposed TLI

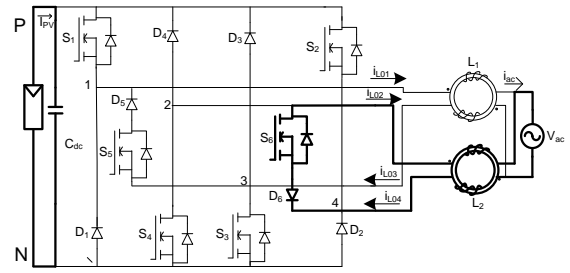


Fig 4 (d) NHC: Freewheeling stage

A. Analysis of the Operational Features for the proposed TLI

The proposed inverter operates in four modes as shown in Fig 4 (a), (b), (c), and (d). During the PHC period from 0s to 0.001s as per PWM pulse generation waveform shown in Fig 8, the switches S1 and S3 are turned ON and the coupled inductor L1 is also activated to supply the load. During the PHC freewheeling period, S5 is conducting through the forward biased diode D5. During the NHC period from 0.002s to 0.003s as per PWM pulse generation waveform shown in Fig 8, the switches S2 and S4 are turned ON and the coupled inductor L2 is also activated to supply the load. During NHC freewheeling period, S6 is conducting through the forward biased diode D6.

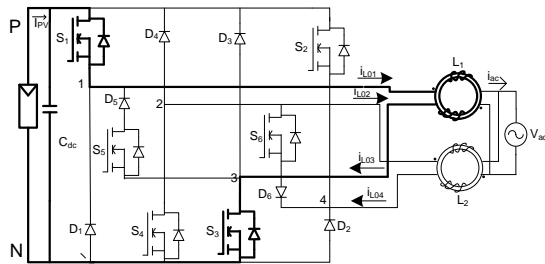


Fig 4 (a) PHC: active stage

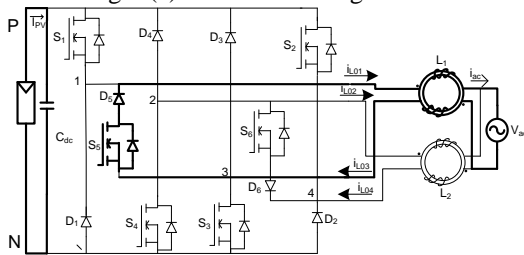


Fig 4 (b) PHC: freewheeling stage

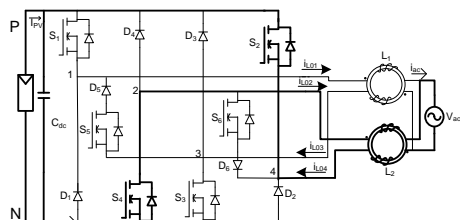


Fig 4 (c) NHC: active stage

B. Analysis of the Leakage Current for the Proposed TLI

The grounding of the grid is connected to PV array through TLIs. The high value of stray capacitance between the PV array and the ground may cause the large value of ground leakage current. A model comprising four output points (1, 2, 3, and 4) is depicted in Fig 5 for analyzing the ground-loop leakage current. These output points are connected to N points, i.e., the negative terminal of the DC bus and modeled as controlled voltage sources.

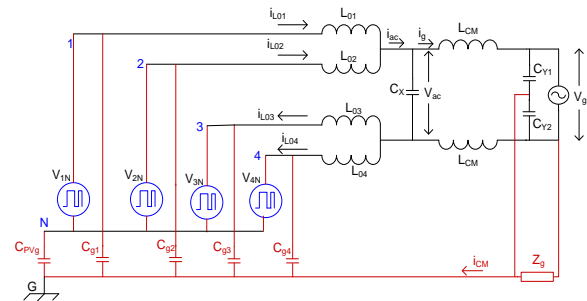


Fig 5 Equivalent circuit diagram for analyzing the leakage current of the proposed TLI

The equivalent circuit in Fig 5 clearly shows the stray components through which the leakage current of the ground can be determined.

The stray elements include: (1) the points of ground connection between the inverter and inter-grid series impedance (Z_g), (2) the stray capacitances between the ground and the inverter output points, i.e., C_{g1} – C_{g4} , and (3) the stray capacitances (C_{PVg}) between the PV array and ground. The model also depicts the CM filter components such as L_{CM} , C_{Y1} , and C_{Y2} along with the capacitor C_x for the differential mode (DM) filters.

The impact of capacitors on the current leakage could be ignored as the values of stray capacitances for MOSFETs, i.e., C_{g1} , C_{g2} , C_{g3} , and C_{g4} are extremely low as compared to the stray capacitance (C_{PVg}) between the PV array and ground. Furthermore, the switches S2, S4, and S6 are not activated throughout the PHC. Therefore, the corresponding controlled voltage sources V_{2N} and V_{4N} can be removed and consequently, the simplified model of the CM leakage current can be determined for the PHC as shown in Fig 6.

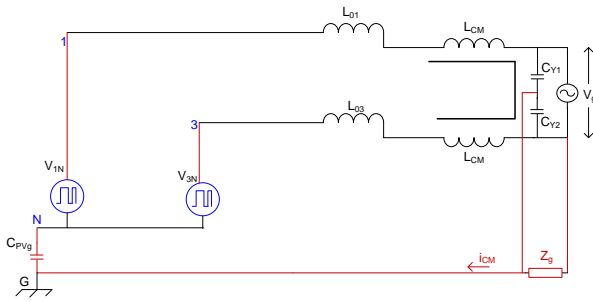


Fig 6 Simplified model for the analysis of the CM leakage current in the PHC

Based on the simplified model of the proposed TLI as shown in Fig 6, a single-loop CM model can be obtained by presenting the equivalent circuits between E and N. Such a single-loop CM model can be represented and used for the analysis of the CM leakage current during the PHC of the proposed TLI. The CM voltage (V_{CM}) can be written as follows:

$$V_{CM} = \frac{V_{1N} + V_{3N}}{2} \quad (1)$$

and the DM voltage (V_{DM}) can be written as:

$$V_{DM} = V_{1N} - V_{3N} \quad (2)$$

The total CM voltage (V_{tCM}) can be defined as follows:

$$V_{tCM} = V_{CM} + V_{DM} \cdot \frac{L_{01} - L_{03}}{2(L_{01} + L_{03})} = \frac{V_{1N} + V_{3N}}{2} + (V_{1N} - V_{3N}) \cdot \frac{L_{01} - L_{03}}{2(L_{01} + L_{03})} \quad (3)$$

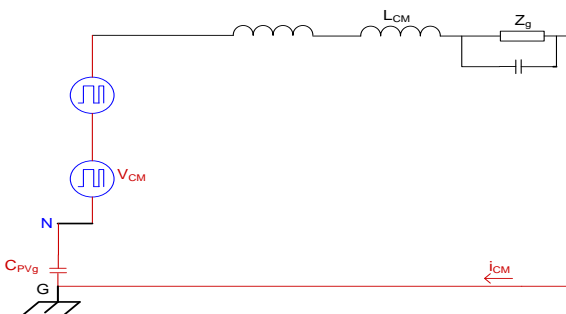


Fig 7 Single-loop CM model for the PHC

From Fig 7, it can be seen that the CM current cannot flow through the converter if the total CM voltage V_{tCM} is kept constant. Generally, $L_{01} = L_{03}$ in a well-structured circuit with symmetrically designed magnetic coils. During the active stage of the PHC, $V_{3N} = 0$ and $V_{1N} = V_{dc}$. With all these relationships, the total CM voltage can be calculated as:

$$V_{tCM} = \frac{V_{1N} + V_{3N}}{2} + (V_{1N} - V_{3N}) \cdot \frac{L_{01} - L_{03}}{2(L_{01} + L_{03})} = \frac{V_{dc}}{2} \quad (4)$$

During the PHC freewheeling stage, i.e., when S1 and S3 are simultaneously turned off, the DC-link voltage is equally shared for which it can be written as:

$$V_{1N} = V_{3N} = \frac{V_{dc}}{2} \quad (5)$$

Therefore, the entire CM voltage throughout the freewheeling is written as follows:

$$V_{tCM} = \frac{V_{1N} + V_{3N}}{2} + (V_{1N} - V_{3N}) \cdot \frac{L_{01} - L_{03}}{2(L_{01} + L_{03})} = \frac{V_{dc}}{2} \quad (6)$$

From the above equations (4) and (6), it is clear that the total CM voltage is fixed throughout the PHC which results in

the non-excitation of the CM current. The amount of the CM leakage current during both PHC and NHC are exactly equal. However, the activation of various components is the only difference in these two modes. Hence, the total CM voltage of the NHC is also $V_{dc}/2$ and the CM ground leakage current will be minimized due to the constant value of the total CM voltage in the entire grid cycle. This has been justified through simulation results in the following section.

IV. PERFORMANCE ANALYSIS OF THE PROPOSED TLI

The performance of the proposed TLI topology is analyzed through both simulation and experimental results is presented here.

A. Simulation Results

The proposed TLI topology for grid-connected PV applications is simulated using MATLAB/Simulink®. The parameters used for the simulation is presented in Table I and the calculation of these parameters are shown in Appendix.,

Table I. System parameters

Grid Frequency f	50 Hz
Grid Voltage	230 V
Switching Frequency	16 kHz
DC Voltage	360 V
Cut-off frequency	1000 Hz
R_d	12 Ω
Inductance L	1.9 mH
C_b	265 μF
C	6 μF

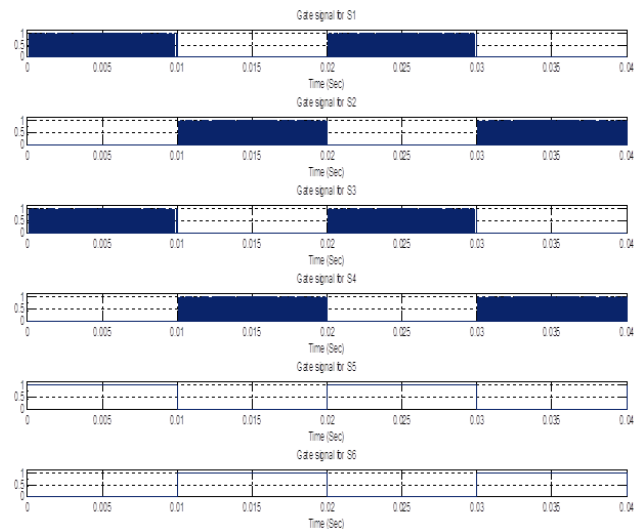


Fig 8. PWM patterns for the proposed TLI.

From Fig 8 the PWM mode switches S1 and S3 (MOSFETs) are activated at the same time as soon as the reference signal ($V_{control}$) crossed zero. Further, S2, S4, and S6 are not active, G2, G4, and G6 (gating signals) are low, and S5 which selects the polarity, is activated in the half grid cycle. Likewise, when the reference signal $V_{control}$ is greater than zero, S2 and S4 (MOSFETs) are activated together in the PWM mode. Further, S1, S3, and S5 are not active, G1, G3, and G5 (gating signals) are low, and S6 is activated in the grid cycle as a polarity selection switch.

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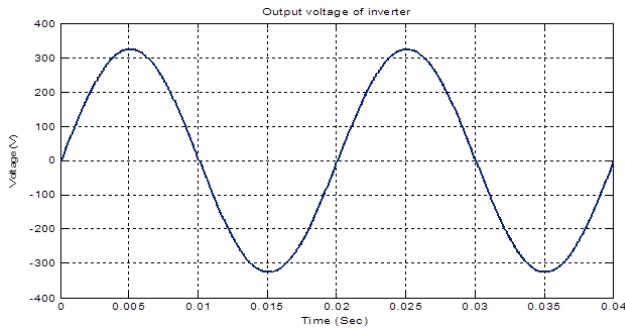


Fig 9. Proposed TLI output voltage.

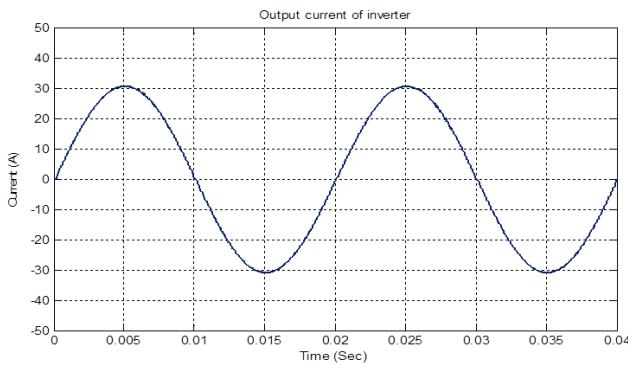


Fig 10 Proposed TLI output current.

The proposed TLI output voltage is depicted in Fig 9. The root mean square value of this voltage matches perfectly with grid voltage to operate as a grid tied single phase inverter. Its output current is depicted in Fig 10. It can be gauged from the figures that with the use of the filter elements' negligible values, the output voltage and the output current are purely sinusoidal in shape. As demonstrated in Fig 11, the THD values are extremely low because of the sinusoidal nature of the current and voltage.

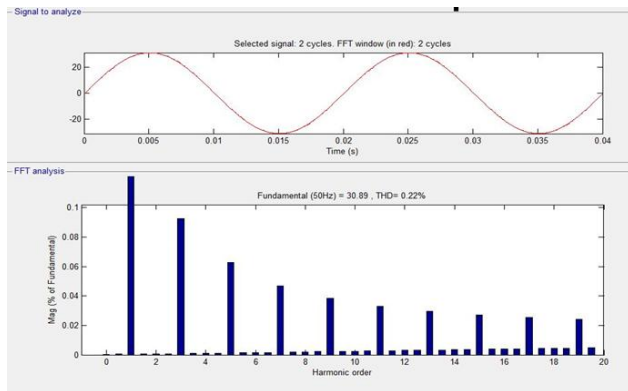


Fig 11 THDs at the output of the proposed TLI

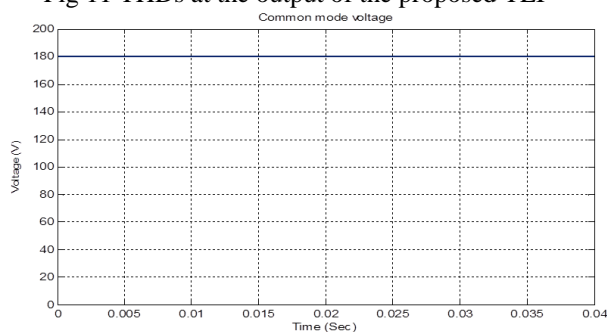


Fig 12 The CM voltage for the proposed TLI

The proposed inverter's (without transformer) CM voltage is depicted as 180V constant voltage in Fig 12., and

the input voltage is twice of the constant voltage, i.e., 360V. The design equation is satisfied by the CM voltage (Fig 12). The leakage currents are less because the CM voltage is maintained as a constant.

V. CONCLUSION

A reliable and majorly efficacious inverter for grid connected PV systems without transformer is planned, examined, and simulated. The equivalent simulation outcomes are mentioned in detail. The reliability is significantly enhanced due to the absence of shoot-through issue. Since dead time is not required in the twin instances of grid cycle zero crossing and PWM switching commutation, a current distortion of a low AC output is attained. The PV array's decoupling from the grid by two extra unidirectional current switches during the zero stages results in low CM current leakage. In order to decrease the passive component's size and to decrease the ripple of output current, the operation of higher switching frequency is allowed.

In the present study, the topologies' efficiency is not computed and the simulations comprise of ideal constituents. However, the efficiency in simulation and the losses for non-active elements can be computed in future by considering the conduction and switching losses for the switching components in Simulink.

APPENDIX

Calculation of parameters for the proposed TLI for the grid-connected PV system

Frequency $f = 50$ Hz, Voltage $V = 230$ V,
Switching Frequency = 16 kHz, DC Voltage = 360V,
Cut-off frequency $f_o = 20 * 50 = 1000$ Hz

$$L = \frac{R_d}{2\pi f_o}$$

$$R_d = 12 \text{ ohm}$$

$$L = \frac{12}{2\pi * 1000} = 1.9 \text{ mH}$$

$$C_b = \frac{1}{2\pi * 50 * 12} = 265 \mu\text{F}$$

$$C = 2.5\% \text{ of } C_b = 0.025 * 265 \mu\text{F} = 6 \mu\text{F}$$

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