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Leakage current mitigation and efficiency enhancement in transformerless 3-level NPC PV inverters

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ABSTRACT

In this research explores the design and performance of a transformerless (TL) three-level neutral point clamped (NPC) inverter for grid-connected photovoltaic (PV) systems. In the push toward more compact, cost-effective, and efficient renewable energy systems, TL inverter topologies have emerged as a strong alternative to conventional systems that use line-frequency transformers. The proposed topology includes two separate PV sources interfaced through dedicated boost converters, which then feed into a common NPC inverter, enhancing flexibility and maximum power point tracking (MPPT) performance. Comprehensive simulations were performed using MATLAB/Simulink to evaluate grid compatibility, total harmonic distortion (THD), and transient behavior under fluctuating irradiance levels. Results validate the efficacy of the system in maintaining grid compliance, lowering leakage current, and achieving high-quality power output. Compared to traditional two-level inverters or transformer-based alternatives, the proposed system demonstrates a clear performance advantage in both efficiency and reliability.

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1. INTRODUCTION

Grid-connected photovoltaic (GC-PV) systems are now an essential part of power generation due to the rising need for renewable energy, as the PV modules convert solar directly into electricity and feed it into the grid [1]. These systems save electricity prices, enable scalable deployments, and enhance energy efficiency by delivering power straight to the grid, improving grid resilience, sustainability, and overall energy security [2]. In order to give power directly to the grid, an inverter component is necessary for transforming photovoltaic (PV), module's direct current (DC), and output into alternating current (AC) power [3]. It guarantees that the transformed power is matched with the frequency and voltage standards of the grid ensuring compatible and stable operation with the utility grid. However, conventional inverters rely heavily upon bulky transformers for galvanic isolation which raises the system's cost, weight, and efficiency losses. To overcome these drawbacks, transformerless (TL) inverters have emerged as a more efficient and compact alternative, especially in residential and commercial PV applications [4], [5].

Grid-connected TL PV inverters offer high efficiency, decreased switching losses, reduced weight and cost-effectiveness because they may be linked directly to the electrical grid without the need for a

transformer [6]. However, the inverters produce common-mode (CM) voltage induced by voltage fluctuations in the stray capacitors of the PV cell, which might result in more leakage current [7], [8]. This leakage current poses a significant risk of electric shock, as it may create unintended conduction paths through parasitic capacitors to the converter ground [9]. To combat this issue, inverter topologies such as neutral point clamped (NPC) and half bridge (HB) have emerged as promising TL solutions that are immune to leakage currents [10]. Of these, NPC inverters which have three levels are the most prominent applications for TL inverter topologies. NPC inverters along with pulse width modulation (PWM) technique reduce output voltage distortion, voltage stress and overall total harmonic distortion (THD) in power equipment working exceptionally well in applications requiring medium to high power [11], [12].

PWM is a vital technique in power electronics for controlling the output of inverters and converters by altering the pulse width to produce the required power [13]. Hysteresis PWM maintains output current within a set band for fast response and selective harmonic elimination eliminates specific harmonics using optimized switching angles. Each PWM method offers unique benefits depending on application requirements, such as power quality, efficiency, and switching losses [14]. However, traditional PWM techniques and standard discontinuous and space vector PWM (SVPWM) are not well efficient in reducing leakage current problems [15]-[18]. Therefore, in the proposed system, space vector modulation (SVM) is employed with 3-level NPC inverters to reduce harmonics and switching losses, balance neutral point voltage, maximize the use of DC-link voltage and improve modulation flexibility that have not been holistically addressed in existing models. The major contributions of the proposed method are:

- A TL 3-level NPC inverter is integrated with two PV systems and boost converters for achieving reduced cost, size, weight, and improved DC-link voltage balancing with the help of neutral point clamping diodes.
- SVM is employed to enhance modulation efficiency, minimize THD, reduce switching losses, and enhance DC-link voltage utilization.
- The proposed 3-level NPC inverted with SVM addressed CM voltage (CMV) and leakage current problems, thereby enhancing system safety.
- The model achieved high efficiency and stable output currents and voltages with low THD ensuring the practical implementation of the proposed system in electrical networks.

The research questions for the proposed method are:

- How can TL three-level NPC inverters with leakage currents be reduced for PV systems that are linked to the grid?
- What techniques can be used to optimize voltage balancing and minimize leakage currents in TL NPC inverters for stable grid integration?
- What impact does SVM have on the performance of a proposed inverter?

2. METHOD

In this section, the proposed 3-level transformerless neutral point clamped (3L-TL-NPC)-SVM is explained and the workflow of the proposed technique in mitigating leakage current is also discussed. Figure 1 represents the block diagram of the proposed 3L-TL-NPC-SVM for leakage current mitigation in grid-tied PV applications. The proposed framework consists of PV systems, maximum power point tracking (MPPT) controllers and DC-DC boost converters configured in two pairs, 3-level NPC inverters and SVM connected to the utility grid. Each PV system consists of two separate solar panels generating DC voltage V_{pv} and DC current I_{pv} directly from sunlight.

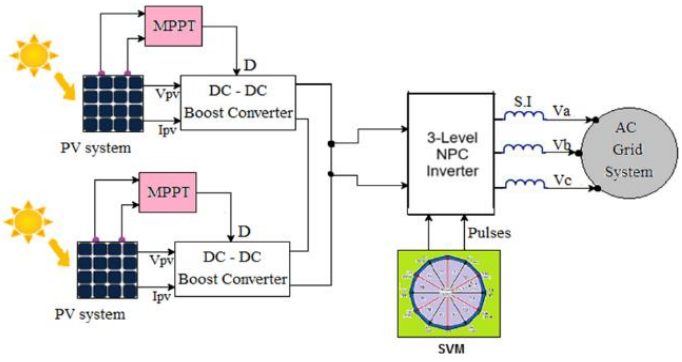

Figure 1. Block diagram of the proposed 3L-TL-NPC-SVM for grid-connected PV applications

Each solar panel is connected to DC-DC boost converters that adjust the voltage and current of solar panels so that PV panels produce maximum power by operating at its maximum power point. The adjustment is done with the help of MPPT controllers that sense the voltage and current of solar panels and changes the duty cycle D of boost converter for adjusting current and voltage of solar panels. The DC-DC boost converters then step up and stabilizes the voltage from solar panels before feeding it to the inverter. The outputs of two boost converters are combined together and given to the 3-level NPC inverter for converting DC voltage to AC voltage suitable for integrating with grid. The inverter's switching network produces three voltage levels, namely $\frac{+V_{dc}}{2}$, 0 and $\frac{-V_{dc}}{2}$. The produced voltages are further used by the inverter for generating three-phase AC signal waveform V_a, V_b, and V_c to form a standard 3-phase AC grid signal. Since the inverter's output voltage levels are discrete, SVM is utilized for creating AC signals by generating switching signals that drive the inverter.

2.1. Photovoltaic system, maximum power point tracking, and DC-DC boost converter

PV modules are used in PV systems to transform solar radiation into DC power [19]. This DC electricity is transformed into AC via an inverter so that grid-connected applications can use it. TL systems use an inverter rather than a transformer to link the solar array to the grid, which reduces weight, cost, and energy losses. The solar cell of a photovoltaic system, which is frequently composed of semiconductor elements like silicon, is its most important component. Electrons in the solar cell are energized by sunlight, which induces an electric current to flow [20]. In order to maintain optimal solar panel performance even in the face of changing external conditions, MPPT aims to continuously track this MPP [21]. In short, the PV system's maximum power output under different environmental circumstances (such as temperature and radiation) is extracted via MPPT. The optimal power output of PV systems is ensured by MPPT, which generally results in a 20–30% increase in energy harvest when compared with those without MPPT [22]. The perturb and observe method, the constant voltage strategy, and the progressive conductivity approach are examples of popular MPPT methods. In the proposed methodology, the maximum DC voltage coming from the 2 DC-DC boost converters are combined and fed to the 3L-TL-NPC inverter.

2.2. 3-level transformerless neutral point clamped inverter

Multilevel inverters for solar panels and other renewable energy sources are made with NPC TL inverters. It offers several advantages, like decreased dimensions, weight, expense, and increased effectiveness, by eliminating the transformer traditionally used in inverters [23]. Three amounts of voltage can be generated by a multilevel inverter of the 3-level NPC type: positive, negative, and zero. In the proposed method, a 3-level inverter is used and the circuit diagram of the 3L-TL-NPC inverter is illustrated in Figure 2.

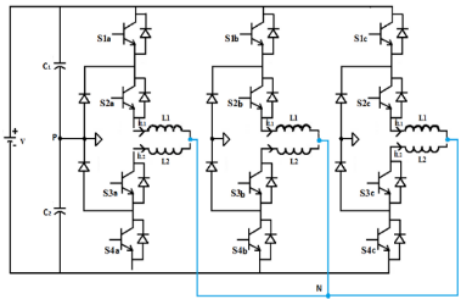

Figure 2. Circuit diagram of TL 3-level NPC inverter

The 3-level NPC inverter uses the combined DC voltage from boost converters to produce a AC signal with three voltage levels, +Vdc/2, 0, and -Vdc/2. The 3-level inverter has three phases that are connected to one line of a 3-phase grid system. Each phase of the 3-level inverter consists of four power switches: two for the positive, two for the negative, and two for every half-cycle to provide the intermediate voltage level, or zero, and to ensure that the voltage levels are balanced. To maintain a stable voltage of 0 V at the neutral point, neutral-point clamping diodes are used. There are three ways a proposed inverter can operate based on the output voltage that is required:

Mode 1: the load is linked to a positive DC bus (+Vdc), and both upper switches (S1 and S2) are in the on position. An output voltage of +Vdc/2 is present.

Mode 2: switches S2 on top and S3 on bottom are both switched on. One clamping diode (D2) is active, Clamping the output to zero by allowing current pass through the neutral point. The load is linked between the DC link's center and neutral point, resulting in an output voltage of 0.

Mode 3: S3 and S4, two lower switches, are activated, connecting the load to the negative DC bus (-Vdc). Neutral-point clamping diodes are not functional in this mode. The voltage at which the output is -Vdc/2. Only with proper grounding and advanced switching techniques, the TL design minimizes leakage current and enhances system safety. In order to minimize leakage current, SVM is used in the proposed model.

2.2.1. Space vector modulation

Inverters with NPC technology function in three stages, which is one of the numerous multilevel inverters that are controlled by the commonly utilized SVM technology. To generate the voltage vectors required for the proposed inverter, SVM determines the proper switching states, guaranteeing effective and balanced operation [24]. SVM generates switching signals for smoothing out the AC voltage produced by inverter, thereby reducing leakage current and harmonics. SVM is based on representing the desired three-phase AC output as a single rotating vector in a two-dimensional space [25]. The inverter switches are modulated to resemble the space vector created by transforming the voltage waveforms (Va, Vb, and Vc) in three phases into a combination of discrete switching states that are available. In the proposed inverter, the space vector diagram has 27 possible switching states as opposed to just 8 for a 2-level inverter, corresponding to three voltage levels per phase. Typically, symmetrical switching patterns are used to reduce stress on the power switches and ensure a smooth voltage waveform. Switching time calculation for 3-level SVM is depicted in Figure 3 neutral point balancing.

After modulating the inverter's signal with switching signals generated by SVM, the approximate sine waves Va, Vb, and Vc produced by the inverter are injected to the 3-phase grid signal. Since the harmonics and leakage current are minimized by the proposed inverter with SVM, the grid signal is free from harmonics.

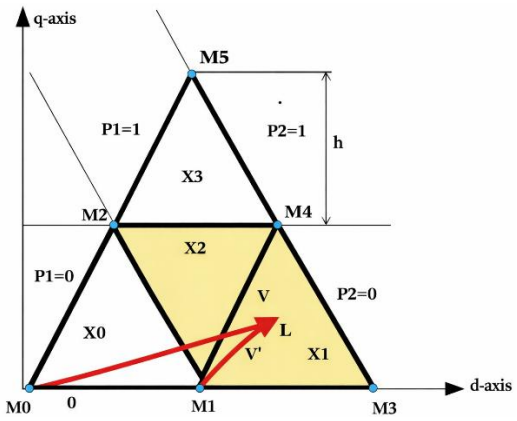

Figure 3. SVM's switching time calculation

3. RESULT AND DISCUSSION

A crucial design for grid-connected PV systems is the TL 3-level NPC inverter, which eliminates the need for huge transformers and has low harmonic distortion and excellent efficiency. The suggested topology ensures dependable grid integration while efficiently minimizing leakage current, increasing voltage stability, and improving power quality by lowering THD. By optimizing switching performance, SVM is also included, which lowers switching losses and boosts efficiency.

The TL 3-level NPC inverter's efficiency is simulated using the MATLAB/Simulink environment. The simulation results of the proposed model are explained in detail and a comparative analysis is also given. Figure 4 shows the Performance analysis of MPPT control and power extraction along with modulation behavior of the NPC inverter under dynamic conditions. The duty cycle of MPPTs 1 and 2 is displayed in Figure 4(a), where D1 and D2 represent the duty cycles obtained from MPPT 1 and MPPT 2 over a short duration of 0–0.1 s. The duty cycle of MPPT is represented by the blue line and the red line represents the duty cycle of MPPT 2. Both D1 and D2 are stabilized rapidly within the initial few milliseconds, demonstrating that the MPPT modules quickly track the MPP of their respective solar sources. Each PV source effectively reaches its ideal operating point after stabilization, as seen by D1 remaining at 0.6 and D2 at 0.5, meaning MPPT 1 and MPPT 2 keep the switch ON 60% and 50% of time respectively. This result shows how well the proposed method works to guarantee that each PV source independently runs at its maximum power point. The system responds rapidly to dynamic situations and efficiently extracts energy without oscillations, as demonstrated by the stable duty cycles. These results are consistent with the system's goal of increasing the flexibility of PV systems and optimizing energy harvesting in the TL inverter configuration.

Figure 4(b) examines the performance of a solar power PV array with 8 modules and 340 V and 320 V open-circuit voltages. The PVs' output power initially starts at 0 s, then rises to 100 W and 101 W after 0.06 s. The modulation index for the NPC inverter is also monitored, reducing distortion if it exceeds the maximum modulation of 1 which is shown in Figure 4(c). The results show that the NPC inverter provides reliable operational performance without exceeding maximum voltage limits, ensuring component protection and system efficiency. The results suggest that the NPC inverter delivers reliable performance without exceeding maximum voltage limits.

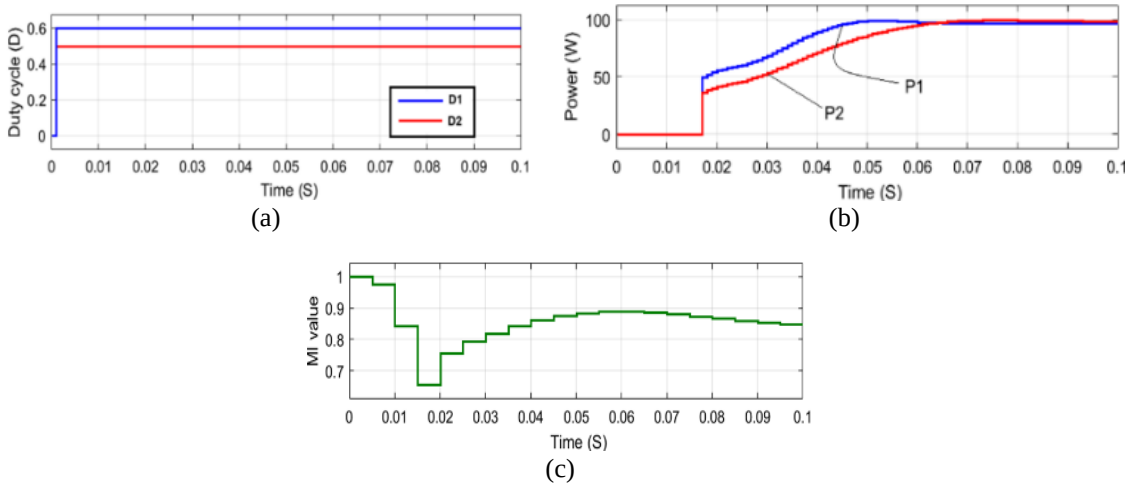

Figure 4. Performance of MPPT control, power extraction, and NPC inverter modulation under dynamic conditions; (a) duty cycle obtained from MPPT 1 and 2, (b) power curve of PV-1 and PV-2, and (c) modulation index variation for NPC inverter

Figure 5 show the dynamic voltage performance of the boost converter and capacitor balancing behavior in the proposed system. The combined output voltage of two boost converters is displayed in Figure 5(a). A steady output voltage of 510 V is obtained after an initial transient (settling) period of 0.025 seconds. During the settling period, the output voltage overshot to about 690 V. The stabilized voltage of 510 V within a short period indicates that the converters are working as intended successfully boosting the input voltage with low ripple and quickly maintaining a steady output voltage. Figure 5(b) displays the voltages VC1 and VC2 across capacitors C1 and C2 respectively. The voltages in each capacitor is monitored to maintain equal voltages across the capacitors for reducing stress. In Figure 5(b), the voltage across C1 capacitor is 254.5 V and C2 capacitor is -255.5 V meaning an imbalance of 1% is present implying the voltage is almost balanced. Even in the transient period (0.025 s), the imbalance is found to be minimum.

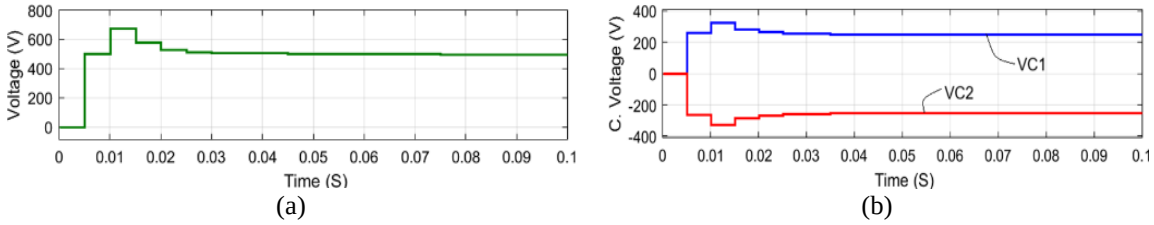

Figure 5. Dynamic voltage performance of the boost converter and capacitor balancing behavior in the proposed system; (a) output voltage from boost converter and (b) voltage across capacitors VC1 and VC2

Figure 6 displays the collective switching pulses for both legs (Legs A and B) of the NPC inverter. The four sub-plots on the left side of Figure 6 indicate the switching pulses for Leg A and each subgraph corresponds to the PWM gate signals controlling the four switching components present in Leg A. On the other hand, the four subgraphs on the right side represent the switching pulses for Leg B and each subgraph portrays the PWM gate signals controlling the four switching devices present in Leg B. The NPC inverter operates at a switching frequency of 10 kHz to minimize switching losses and harmonics. Leg B's pulses are similar to Leg

A's pulses but are phase-shifted for the production of multi-phase output voltages ensuring the supply of three-phase output voltages for integrating PVs with the grid. With the help of the switching signals produced by SVM, the four switches in each leg are turned ON and OFF producing an output AC voltage by taking the three voltage levels from DC bus thereby balancing neutral point and reducing harmonics. This coordinated switching mechanism of 3-level inverters is better than the conventional two-level inverters.

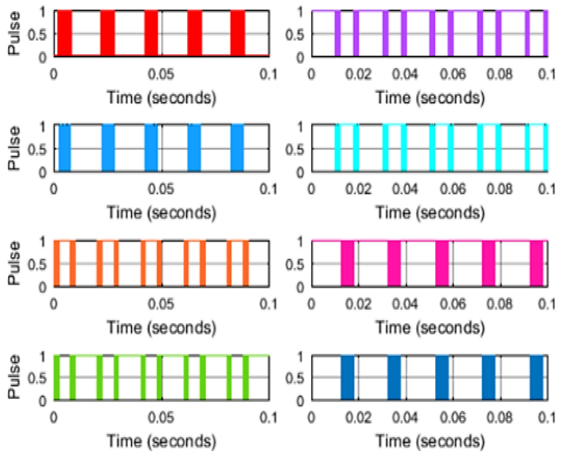

Figure 6. Switching pulses for Leg A and B of NPC inverter

The Figure 7 shows the output current waveform of a three-phase 3-level NPC inverter and each subgraph represents the output waveform for each phase of the 3-phase signal. The switching signals of the inverter produced these stepped signals with a peak voltage of 509.5 V. The waveforms are stepped because of the switching of 3 voltage levels for producing an AC signal like waveform with less harmonics.

Figure 8 depicts the control of CMV during voltage sag conditions with the help of SVM optimized switching. During voltage sag period, the uncontrolled CMV denotes the rise in CMV because of SVM straining and the controlled CMV denotes the reduced CMV achieved by optimizing SVM switching states. Since SVM tries to match the grid voltage with inverter output voltages, both are denoted by the same green line in the figure. Normally, the grid nominal voltage is 1, and the inverter output uses SVM to match this value. Grid voltage falls to 0.7 during voltage sags. After that, SVM tries to synchronize, increasing leakage current and CMV to 0.32. CMV is kept to 0.02 by optimizing SVM switching, which lowers leakage current and allows for synchronization at 0.7 grid voltage.

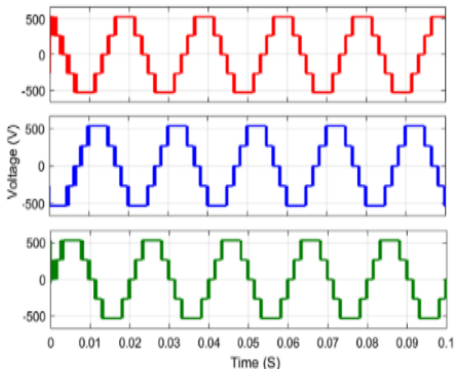

Figure 7. Output current of 3-phase 3-level NPC inverter

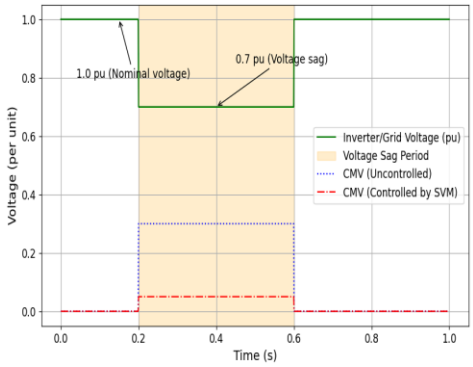

Figure 8. CMV control by optimizing SVM switching during grid voltage sags

Figure 9 illustrates the leakage current profiles of various TL inverter control techniques including super twisting-based sliding mode control (ST-SMC) [25], model-free predictive control (MFPC) [24], TL T-type NPC multilevel inverter (TL-TNPC-MLI) [12] and modified synchronized SVPWM (MS-SVPWM) [19] and the proposed 3L-TL-NPC-SVM models. In the figure, the dashed horizontal line denotes the RMS value of leakage currents, which provides an overall measure of the total leakage over a certain period. ST-SMC [25]

produced the highest leakage current of 0.46 A; MFPC [24] 0.29 A, TL-TNPC-MLI [23] 0.26 A and MS-SVPWM [19] 0.22 A, while the proposed 3L-TL-NPC-SVM inverter achieved the lowest leakage current of 0.08 A. The reduction is due to SVM switching, undoubtedly confirming the proposed model's effectiveness in minimizing leakage currents.

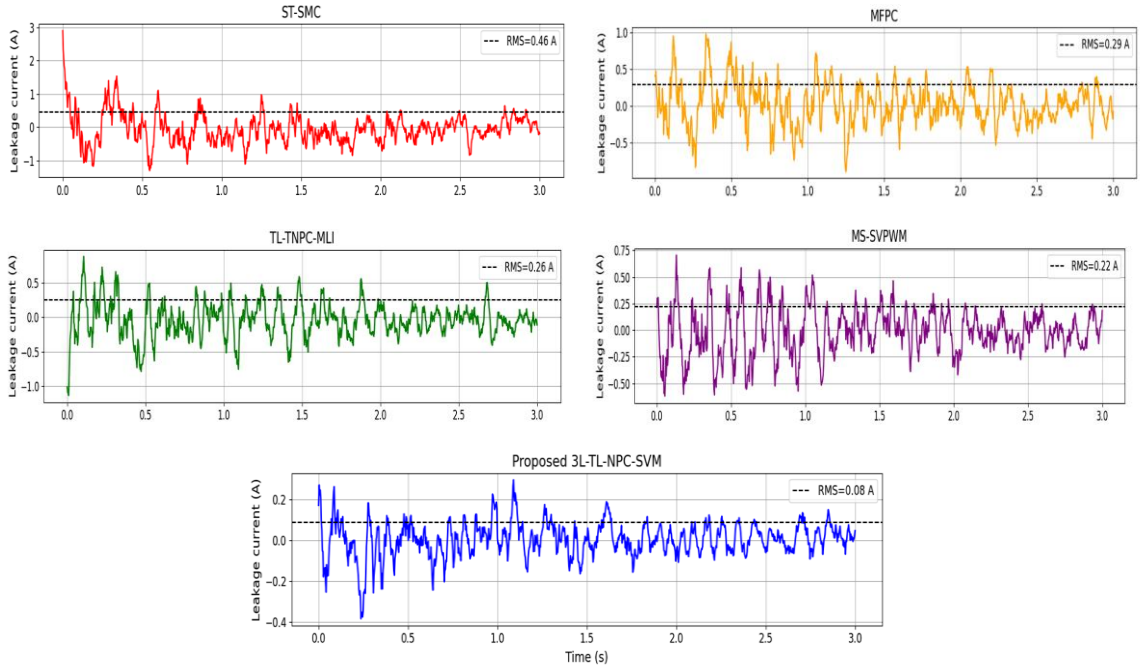

Figure 9. Leakage current comparison of various inverter topologies

The proposed inverter is compared against conventional two-level and transformer-based inverters for efficiency, leakage current and THD and the results are presented in Table 1. For ensuring fair comparison, the three inverters are simulated under identical testing scenarios including identical PV power profile, temperature, solar irradiance, grid voltage, and load conditions. Each inverter is also employed identical MPPT algorithms. Besides, the simulation durations are also matched to prevent disparities brought on by transient startup effects.

From the Table 1, it is clear that the THD and leakage current of transformer-based inverters are lower than the two-level as well as the proposed models. It is because transformer-based inverters provide galvanic isolation. So, in order to reduce the weight and cost only, new inverters are being developed. However, the THD and leakage current of the proposed inverter is lower than the two-level inverters. Besides, the proposed technique excels in having high efficiency than the two benchmark techniques.

Table 1. Performance comparison of benchmark inverters and proposed 3L-TL-NPC-SVM

Performance metrics	Two-level inverter	Transformer-based inverter	Proposed 3L-TL-NPC-SVM
Efficiency (%)	93	95	97
THD (%)	7	2.6	3.78
Leakage current (A)	4	0.02	0.08

Figure 10 depicts the THD values of different inverter topologies describing how each inverter's output wave is similar to an ideal sine waveform. The THD values of the conventional inverters, such as ST-SMC [25], MFPC [24], TL-TNPC-MLI [23], and MS-SVPWM [19] are found to be 6%, 5.55, 5.3%, and 4.6%. But the proposed 3L-TL-NPC-SVM inverter produced an output signal that closely resembles the ideal sine wave, thereby having a lower THD of 3.78%.

3.1. Discussion

The proposed 3L-TL-NPC-SVM solar PV system significantly reduces leakage current to 0.08 A, outperforming existing models. The system achieves quick duty cycle stabilization through dual MPPT units, allowing each PV module to function efficiently at its maximum power point. The system also achieves output

current quality and modulation index, ensuring AC waveforms free from distortion suitable for grid integration. However, the system has limitations, such as being mostly validated under steady sun radiation, increasing hardware complexity and cost, and being evaluated through short-duration simulations without hardware implementation. Future studies should focus on improving the system's resilience to abrupt changes in irradiance and partial shading, using cost-performance trade-off analysis and hardware design optimization. More mitigation can be achieved using sophisticated control techniques, such as optimized zero-sequence voltage injection or predictive modulation. System-level solutions like CM filters, residual current detectors, and ground monitoring equipment can also provide additional security.

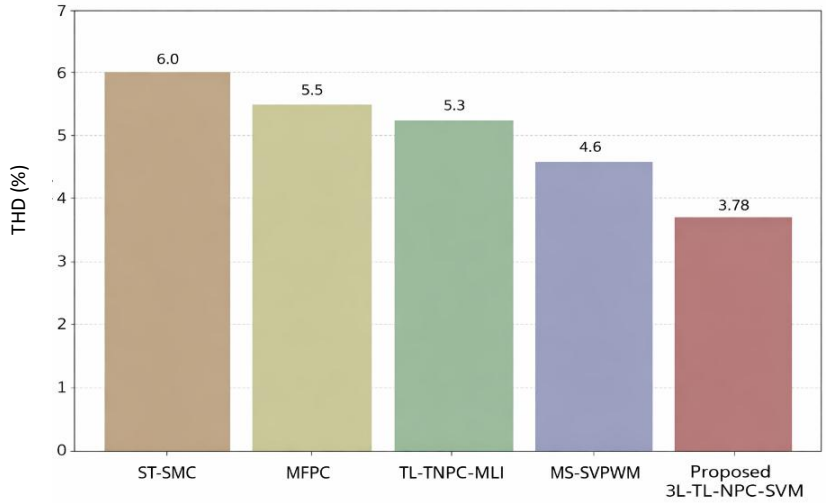

Figure 10. THD comparison of various inverter techniques

4. CONCLUSION

Grid-connected PV systems and TL 3-Level NPC inverters are potential solutions for renewable energy applications that are both high-performing and efficient. The proposed system operated with 2 PV system with boost converter fed 3-level NPC inverter. Use of neutral point clamping diodes ensures stable voltage balancing across the DC-link capacitors, while leakage currents are minimized to meet safety regulations. MATLAB/Simulink is utilized to confirm the suggested TL three-level NPC inverter's functionality. Additionally, the inverter synchronizes effectively with the grid, ensuring stable power injection even under fluctuating environmental conditions. The results of the simulation reveal that the suggested inverter exhibits enhanced power quality with a lower THD of 3.78%, high efficiency, low harmonic distortion, and good voltage stability analysis. Efficiency assessments also point to reduced leakage currents and improved power conversion. The leakage current mitigation is achieved by reducing CMV through the optimization of SVM's switching states rather than simply reducing harmonic content. This makes it possible to construct safer TL inverters without using large isolation transformers. Overall, the 3-level NPC inverter is a very practical method to enhance the incorporation of renewable energy sources into electrical networks and helps to ensure the efficient, dependable, and secure functioning of PV systems. Although simulations under constant irradiance are the basis for the current evaluation, future work should include hardware prototypes, cost-performance optimization and evaluation under partial shading and a variety of grid situations. These developments might make the proposed design even more applicable for large-scale smart grid and renewable energy applications.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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