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# A Comprehensive Review Control Techniques for Transformer-Less Inverters in Grid-Connected PV System

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**Abstract:** The increasing demand for a higher standard of living has significantly boosted global electrical energy consumption. This growing demand, along with the depletion of fossil fuels and environmental concerns, has accelerated the adoption of renewable energy technologies. Among them, photovoltaic (PV) systems have emerged as a key green energy source. The inverter, a crucial interface between the PV array and the grid, can be either transformer-isolated or transformer-less. Recently, single-phase transformer-less voltage source inverters (VSIs) have become popular in distributed PV grid-connected systems due to their high efficiency and compact design. This paper reviews notable transformer-less inverter topologies and proposes a new configuration. The proposed inverter is analyzed and validated through MATLAB/Simulink simulations

**KEYWORDS:** Photovoltaic (PV), Transformer less, Inverter

## I. INTRODUCTION

The continuous pursuit of improved living standards has led to a remarkable rise in global electrical energy consumption. This increase, combined with the depletion of conventional fossil fuel resources and escalating environmental challenges, has intensified the global transition toward sustainable and renewable energy systems. Among the various renewable options, photovoltaic (PV) technology has emerged as one of the most promising solutions, contributing significantly to the clean energy sector. A fundamental element in any PV system is the inverter, which converts DC power from solar panels into AC power suitable for grid integration. Inverters are typically classified into two categories: transformer-isolated and transformer-less (non-isolated) types. In recent years, single-phase transformer-less voltage source inverters (VSIs) have gained widespread use in distributed PV grid-connected systems owing to their improved efficiency, compact structure, and lower cost. This paper presents a review of significant transformer-less inverter topologies and introduces a novel inverter configuration. The proposed design is analyzed and verified through MATLAB/Simulink simulation to demonstrate its effectiveness and performance benefits

The rapid growth of the global population and the depletion of conventional energy resources such as coal, oil, and natural gas have intensified the search for alternative and sustainable energy sources. Among various renewable options, solar energy has gained remarkable attention due to its abundance, cleanliness, and inexhaustible nature. The utilization of solar photovoltaic (PV) systems has increased significantly in recent years, driven by declining PV module costs, technological advancements, and supportive government policies promoting green energy adoption[1].

With the global demand for electricity rising rapidly, grid-connected PV systems have become an essential component of modern distributed power generation[2]. Continuous advancements in power electronics and semiconductor technologies have played a crucial role in improving the efficiency and reliability of these systems. A key component in any PV system is the power inverter, which converts the DC power generated by solar panels into AC power suitable for grid integration. Depending on their configuration, grid-tied PV inverters can be broadly classified into two categories: transformer-isolated and transformer-less (non-isolated) systems[4].



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Traditionally, transformer-based inverters have been widely used to provide galvanic isolation between the PV array and the utility grid, ensuring safety and preventing DC current injection[5]. The galvanic isolation minimizes leakage current, enhances user protection, and meets grid safety standards. High-frequency transformers are often employed on the DC side, while low-frequency transformers are placed at the AC output side of the inverter. However, these transformers introduce several drawbacks, such as increased system cost, weight, volume, and reduced efficiency due to additional power losses in the magnetic components[6].

To overcome these limitations, researchers have focused on transformer-less (TL) inverter topologies. TL inverters eliminate the bulky transformer, resulting in higher efficiency, compact design, reduced cost, and lightweight structure. Despite these advantages, TL inverters face technical challenges such as ground leakage current, DC injection, and electromagnetic interference (EMI), which can affect grid stability and safety. Hence, innovative inverter topologies and advanced control strategies are essential to address these issues effectively[7].

In this context, the present work focuses on the analysis, modeling, and closed-loop operation of a novel transformer-less inverter topology for single-phase grid-connected PV applications. The proposed design utilizes unipolar pulse width modulation (PWM) control, which effectively minimizes ground leakage current and improves conversion efficiency. The inverter exhibits several distinct advantages:

- (i) elimination of ground leakage current,
- (ii) buck–boost voltage regulation capability,
- (iii) enhanced operational lifespan,
- (iv) efficient maximum power extraction through MPPT,
- (v) low total harmonic distortion (THD) of output current, and
- (vi) minimal DC current injection into the grid.

The study also includes small-signal modeling (SSA), controller design, and the integration of MPPT and Phase-Locked Loop (PLL) using inverse Park transformation to ensure stable grid synchronization and dynamic performance improvement.

## II. LITERATURE SURVEY

In recent years, extensive research has been carried out on transformer-less inverter topologies for single-phase grid-connected photovoltaic (PV) systems to enhance conversion efficiency and reduce system cost. Transformer-less configurations eliminate bulky magnetic components, making the system compact and lightweight. However, the absence of galvanic isolation introduces challenges such as ground leakage current, DC injection, and safety concerns, which must be addressed through appropriate circuit design and control strategies.

Several transformer-less inverter topologies have been proposed to mitigate leakage current while maintaining high efficiency. The H5 inverter, introduced by SMA, incorporates an additional DC-side switch to disconnect the PV array during freewheeling intervals, reducing leakage current. The H6 inverter further improves upon this by employing two additional switches to achieve better common-mode voltage control. Similarly, the HERIC (Highly Efficient and Reliable Inverter Concept) topology introduces auxiliary switches in the AC side to provide freewheeling paths and minimize common-mode voltage variations. Other configurations, such as the HB-ZVR, Conergy-NPC, and Full-Bridge with DC Bypass, have also been reported to enhance performance and safety in grid-tied PV applications.

Beyond topology design, control techniques play a critical role in ensuring stability, dynamic response, and power quality in grid-connected systems. The conventional Proportional–Integral (PI) controller has been widely used for current and voltage regulation due to its simplicity and ease of implementation. However, PI control suffers from limitations such as slow response under varying irradiance and temperature conditions, poor robustness to parameter variations, and steady-state errors during grid disturbances.

To overcome these drawbacks, advanced control methods have been explored. Pulse Width Modulation (PWM) techniques, particularly unipolar PWM, are employed to minimize ground leakage current and reduce switching losses. Sliding Mode Control (SMC) has gained attention for its inherent robustness, fast transient response, and strong disturbance rejection capability. SMC-based control strategies effectively handle system nonlinearities and uncertainties, making them suitable for transformer-less PV inverters under fluctuating environmental conditions. Furthermore, adaptive and intelligent control techniques, such as Fuzzy Logic, Artificial Neural Networks (ANNs), and



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Adaptive Neuro-Fuzzy Inference Systems (ANFIS), have been integrated to enhance inverter performance, dynamic stability, and grid compliance.

Despite these developments, challenges remain in achieving a trade-off between efficiency, leakage current suppression, harmonic distortion, and control complexity. Most existing topologies either involve a higher number of switches or require complex modulation schemes, which affect cost and reliability. Hence, there is a continuous need for a simplified, efficient, and reliable inverter topology that ensures low leakage current, reduced THD, and high power quality while maintaining grid synchronization and operational stability.

To address these challenges, the present work proposes a novel transformer-less inverter topology with an advanced closed-loop control mechanism. The proposed design combines the advantages of efficient switching control, reduced common-mode voltage variation, and enhanced grid synchronization. Simulation studies are carried out in MATLAB/Simulink to validate its effectiveness in terms of leakage current suppression, harmonic reduction, and overall system efficiency under varying solar and grid conditions

### III. PROBLEM FORMULATION

#### Existing System

Existing system with H5 transformer less system available but is the most versatile device. In summary, the H5 topology has the best leakage current characteristic, but its efficiency is the lowest. The H6 topology has the best performance about leakage current suppression in existing single-phase full-bridge transformer see topologies but high leakage current.

#### Proposed System

The overall configuration of the proposed single-phase grid-connected photovoltaic (PV) system is illustrated in Fig. 1. The system primarily consists of a PV array, a DC/DC boosting stage with DC/AC conversion, a control unit, and the utility grid with local load connection. The integrated control structure ensures efficient energy extraction from the PV array, power quality improvement, and stable grid synchronization.

#### Photovoltaic (PV) Array

The PV array serves as the primary energy source by converting incident solar radiation into electrical energy. The output voltage  $V_{PV}$  and current  $i_{PV}$  depend on the solar irradiance and temperature. To ensure optimal energy utilization, the PV system must operate at its Maximum Power Point (MPP), which varies with environmental conditions.

#### Maximum Power Point Tracking (MPPT)

An MPPT algorithm is employed to continuously extract the maximum available power from the PV array. In this study, a Perturb and Observe (P&O) or Incremental Conductance (INC) method can be used due to their simplicity and effectiveness. The MPPT controller adjusts the duty ratio of the DC/DC converter to regulate the PV operating voltage  $V_{PV}$  near its MPP, ensuring maximum energy conversion efficiency

#### DC/DC Boosting and DC/AC Conversion

The power conversion unit performs both DC voltage boosting and DC/AC inversion functions. The DC/DC boost converter raises the PV voltage to a suitable DC link level for the inverter operation. The transformer-less inverter then converts this regulated DC voltage into AC power synchronized with the utility grid. The inverter operates under unipolar Pulse Width Modulation (PWM) control, which effectively reduces switching losses and minimizes ground leakage current. This modulation scheme enhances efficiency while maintaining a sinusoidal current waveform with low Total Harmonic Distortion (THD).

#### Grid and Load Interface

The inverter output is connected to the utility grid and local load through an LC filter, which attenuates high-frequency switching components. The system delivers active power to the grid while maintaining voltage and current quality within the prescribed IEEE 519 standards.

The overall control loop ensures that the inverter contributes to grid stability by maintaining synchronization, minimizing harmonic distortion, and avoiding DC injection. The proposed configuration, therefore, offers high efficiency, low leakage current, and reliable grid interfacing suitable for transformer-less PV application

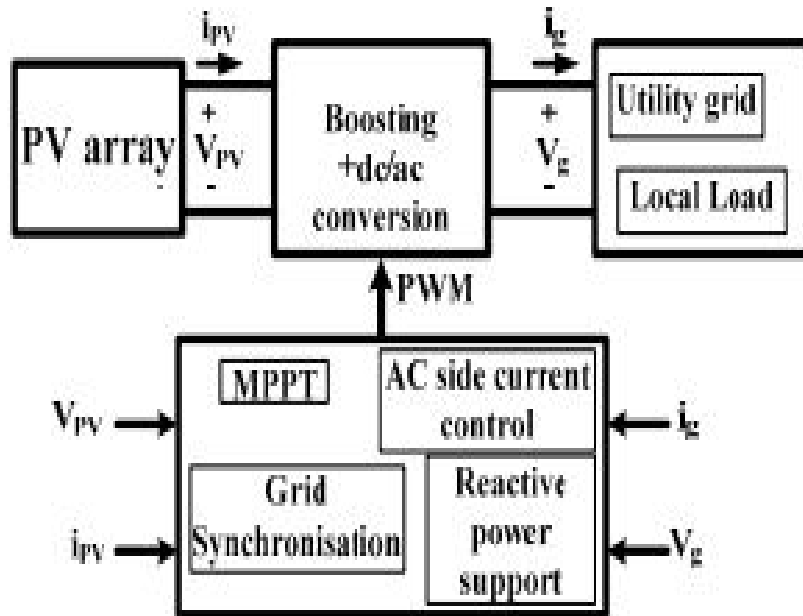


Fig:1 Proposed System

#### IV. VARIOUS CONTROL TECHNIQUES

##### Proportional–Integral (PI) Controller

Purpose: Used for DC-link voltage regulation and current control in grid-connected PV systems.

Working Principle:

The PI controller compares the measured variable (e.g., DC-link voltage or grid current) with its reference value.

The proportional (P) part provides immediate response to the error.

The integral (I) part eliminates steady-state error by integrating the error over time.

Applications:

Regulating the DC-link voltage to ensure stable power flow from PV array to inverter.

Controlling active and reactive power exchange with the grid.

Advantages:

Simple to design and implement.

Suitable for linear and slowly varying systems.

Limitations:

Performance deteriorates under nonlinearities or parameter variations.

Not ideal for systems with rapid disturbances (e.g., sudden irradiance changes).

##### Pulse Width Modulation (PWM)

Purpose: To generate switching signals for inverter power devices (e.g., MOSFETs/IGBTs) for efficient DC–AC conversion.

Common Techniques:

Unipolar PWM: Reduces harmonic distortion and switching losses; commonly used in transformer-less PV inverters.

Bipolar PWM: Simpler but produces higher total harmonic distortion (THD).

Sinusoidal PWM (SPWM): Reference sinusoidal waveform is compared with a high-frequency triangular carrier wave to generate gating pulses.

Space Vector PWM (SVPWM): Advanced method offering higher DC bus utilization and lower harmonics.

Advantages:

Excellent output waveform quality.



High efficiency and easy digital implementation.

Limitations:

Switching losses increase with higher carrier frequency.

May require additional filters to remove high-frequency harmonics.

### Proposed Sliding Mode Control (SMC)

Purpose: Provides robust nonlinear control for current and voltage regulation under disturbances and parameter variations.

Working Principle:

The controller defines a sliding surface that represents the desired dynamic behavior of the system.

The control law drives system states to this surface and maintains motion along it.

In a PV inverter, SMC maintains the output current synchronized with the grid voltage while suppressing leakage current.

Advantages:

Strong robustness against parameter uncertainty and external disturbances.

Fast dynamic response and high accuracy.

Can handle nonlinear characteristics of PV and inverter systems effectively.

The proposed control system consists of several key subsystems, namely grid synchronization, AC-side current control, reactive power support, and PWM generation.

Grid Synchronization:

A Phase-Locked Loop (PLL) using the inverse Park transformation ensures proper phase alignment between the inverter output voltage and the grid voltage  $V_{gV\_gVg}$ . This enables stable and seamless power transfer to the grid.

AC-Side Current Control:

The current control loop regulates the inverter output current  $igi\_gig$  to follow the reference signal derived from the MPPT and grid voltage. This ensures that the injected current is sinusoidal and in phase with the grid voltage, thereby achieving unity power factor operation.

Reactive Power Support:

The control system can also manage reactive power flow to support grid voltage regulation and improve power quality, especially under varying load or grid conditions.

## V. CONCLUSION

This paper reviewed various transformer-less inverter topologies and control strategies for single-phase grid-connected PV systems. Among the studied methods, Sliding Mode Control (SMC) provides superior dynamic response, robustness, and reduced ground leakage current compared to conventional PI and PWM techniques. The proposed inverter topology ensures high efficiency, low THD, and reliable grid synchronization using PLL and MPPT algorithms. Overall, SMC-based closed-loop control offers a promising solution for efficient and stable operation of transformer-less PV systems in modern smart-grid applications.

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