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AN INTELLIGENT HYBRID TRANSFORMERLESS SOLAR PV GRID-CONNECTED INVERTER FOR REACTIVE POWER MANAGEMENT AND LEAKAGE CURRENT MINIMIZATION

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PROBLEM STATEMENT

The increasing deployment of single-phase grid-connected solar photovoltaic (PV) systems has created a demand for highly efficient, reliable, and compact inverter topologies. Conventional transformer-based PV inverters provide galvanic isolation but suffer from high cost, increased size, weight, and reduced efficiency. Although transformer-less inverters offer improved efficiency and reduced system complexity, they are prone to common-mode leakage currents caused by parasitic capacitance between the PV array and ground. These leakage currents can lead to safety hazards, electromagnetic interference (EMI), reduced system reliability, and non-compliance with grid standards. Furthermore, many existing transformer-less inverter topologies have limited capability to supply or absorb reactive power, making it difficult to support grid voltage regulation and power quality. Therefore, there is a need for a hybrid transformer-less grid-connected inverter that can simultaneously minimize leakage current, provide reactive power compensation, improve power quality, and maintain high conversion efficiency under varying operating conditions.

OBJECTIVES

1. To design a hybrid single-phase transformer-less solar photovoltaic grid-connected inverter with enhanced efficiency and compact structure.
2. To reduce common-mode leakage current through an improved inverter topology and advanced switching strategy.
3. To enable reactive power injection and absorption for effective grid voltage support and improved power factor.
4. To implement Maximum Power Point Tracking (MPPT) for maximizing solar energy extraction under varying environmental conditions.
5. To improve power quality by reducing Total Harmonic Distortion (THD) in the inverter output current.
6. To achieve stable synchronization between the PV inverter and the utility grid under dynamic operating conditions.
7. To enhance the overall reliability, safety, and fault ride-through capability of the grid-connected PV system.
8. To validate the proposed inverter performance through simulation by evaluating efficiency, leakage current reduction, reactive power capability, and compliance with grid standards.

ABSTRACT

The increasing adoption of photovoltaic (PV) systems has accelerated the demand for efficient, reliable, and cost-effective grid-connected inverter topologies. Transformer-less inverters have emerged as an attractive solution due to their high efficiency, reduced size, lower cost, and improved power density. However, these systems are susceptible to common-mode leakage current, which affects safety, electromagnetic compatibility, and overall system performance. This paper presents a **hybrid single-phase transformer-less solar photovoltaic grid-connected inverter** capable of providing **reactive power support** while significantly reducing leakage current. The proposed inverter topology combines an optimized switching configuration with an advanced control strategy to ensure efficient power conversion, stable grid synchronization, and compliance with grid interconnection standards. Maximum Power Point Tracking (MPPT) is employed to maximize solar energy extraction under varying environmental conditions, while the inverter simultaneously injects active power and compensates reactive power to improve grid voltage regulation and power factor. Furthermore, the proposed modulation technique effectively suppresses common-mode voltage variations, thereby minimizing leakage current without compromising conversion efficiency. Simulation results demonstrate that the proposed inverter achieves low Total Harmonic Distortion (THD), enhanced power quality, high conversion efficiency, excellent reactive power capability, and stable operation under different irradiance and load conditions. The hybrid transformer-less inverter offers a practical and efficient solution for modern residential and distributed solar PV applications, supporting smart grid integration with improved safety, reliability, and energy utilization.

Keywords: Solar Photovoltaic System, Transformer-less Inverter, Grid-Connected Inverter, Reactive Power Compensation, Leakage Current Reduction, Maximum Power Point Tracking (MPPT), Power Quality, Common-Mode Voltage, Total Harmonic Distortion (THD), Renewable Energy Integration.

INTRODUCTION

The increasing demand for clean and sustainable energy has accelerated the deployment of solar photovoltaic (PV) systems in residential, commercial, and industrial applications. Among various PV integration technologies, **grid-connected transformer-less inverters** have gained significant attention due to their high efficiency, compact size, reduced cost, and lightweight structure compared to conventional transformer-based inverters. By eliminating the line-frequency transformer, transformer-less inverters improve power conversion efficiency and reduce installation costs. However, the absence of galvanic isolation introduces challenges such as common-mode (CM) leakage current, electromagnetic interference (EMI), and safety concerns, which can degrade system performance and limit compliance with international grid standards.

To address these issues, hybrid transformer-less inverter topologies have been developed to minimize leakage current while maintaining high conversion efficiency and reliable grid integration. The integration of **reactive power capability** further enhances the functionality of the inverter by enabling voltage support, power factor correction, and compliance with modern grid codes. This feature allows the photovoltaic system not only to inject active power generated from solar energy but also to compensate for reactive power demand, thereby improving overall grid stability and power quality.

The proposed hybrid single-phase transformer-less solar PV grid-connected inverter combines an advanced inverter topology with an intelligent control strategy to achieve efficient active and reactive power management while significantly reducing leakage current. The control algorithm ensures accurate Maximum Power Point Tracking (MPPT), stable grid synchronization, and effective regulation of inverter output under varying solar irradiation and load conditions. Additionally, the hybrid topology suppresses common-mode voltage variations, resulting in lower leakage current and improved system safety.

Simulation and performance evaluation demonstrate that the proposed inverter provides excellent dynamic response, reduced Total Harmonic Distortion (THD), enhanced power quality, improved power factor, and effective leakage current suppression. Consequently, the proposed system offers a reliable, cost-effective, and high-efficiency solution for next-generation transformer-less photovoltaic grid-connected applications, supporting the growing penetration of renewable energy into modern smart grids.

LITERATURE REVIEW

The increasing penetration of solar photovoltaic (PV) systems into modern power grids has accelerated research on **single-phase transformer-less grid-connected inverters** due to their high efficiency, compact size, reduced cost, and improved power density. However, transformer-less topologies face significant challenges, including **common-mode leakage current, limited reactive power support, and compliance with grid power**

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quality standards. Consequently, researchers have proposed various inverter configurations and advanced control strategies to overcome these limitations while enhancing system reliability and efficiency.

Early transformer-less inverter topologies such as the **H5, HERIC, H6, and Neutral Point Clamped (NPC)** inverters focused primarily on reducing common-mode leakage current through appropriate switching states and modulation techniques. Although these topologies achieved considerable leakage current reduction, they often required additional semiconductor devices, experienced increased switching losses, and offered limited capability for reactive power compensation under varying grid conditions.

Subsequent research introduced hybrid inverter topologies that combine the advantages of conventional full-bridge inverters with additional switching networks to improve operational flexibility. These hybrid configurations effectively suppress leakage current while maintaining high conversion efficiency and enabling bidirectional reactive power flow. Advanced Pulse Width Modulation (PWM) techniques and current control algorithms further improved harmonic performance and dynamic response during grid disturbances.

Recent developments have emphasized **multifunctional grid-connected PV systems** capable of performing active power injection, reactive power compensation, harmonic mitigation, and voltage support simultaneously. Intelligent control methods, including synchronous reference frame control, proportional-resonant (PR) controllers, model predictive control (MPC), and adaptive current controllers, have significantly enhanced inverter performance under changing irradiation, load variations, and grid voltage fluctuations. These approaches improve grid stability while satisfying modern grid codes.

Another major research direction focuses on minimizing leakage current by maintaining a constant common-mode voltage. Novel switching strategies and optimized converter structures have demonstrated substantial reductions in leakage current without sacrificing conversion efficiency. At the same time, reactive power capability has become an essential feature for supporting voltage regulation and improving power factor in distribution networks with high renewable energy penetration.

Despite these advancements, several challenges remain, including increased control complexity, higher implementation costs, thermal stress on switching devices, and maintaining high efficiency under partial-load conditions. The proposed **hybrid single-phase transformer-less solar photovoltaic grid-connected inverter** addresses these issues by integrating an optimized hybrid inverter topology with an advanced control strategy that simultaneously achieves reduced leakage current, enhanced reactive power capability, improved power quality, lower Total Harmonic Distortion (THD), and higher overall system efficiency. The proposed approach provides a reliable and cost-effective solution for next-generation residential and commercial grid-connected photovoltaic applications.

EXISTING SYSTEM

Conventional single-phase transformer-less grid-connected photovoltaic (PV) inverters are widely used because of their high efficiency, reduced size, and lower cost. However, these systems primarily focus on injecting active power into the utility grid and have limited capability to provide ancillary grid support services. Most existing topologies suffer from significant common-mode (CM) leakage current due to the parasitic capacitance between the PV array and ground, leading to safety concerns and electromagnetic interference (EMI). In addition, reactive power compensation is either unavailable or requires additional power conditioning circuits, increasing system complexity. During grid voltage variations, conventional inverters exhibit degraded power quality, higher Total Harmonic Distortion (THD), and limited compliance with modern grid codes. Furthermore, separate control schemes for active and reactive power increase computational burden and reduce overall system efficiency.

Disadvantages of Existing System

- High common-mode leakage current due to transformer-less configuration.
- Limited or no reactive power support capability.

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- Increased harmonic distortion under varying operating conditions.
- Poor voltage regulation during grid disturbances.
- Additional converters or filters are required for power quality improvement.
- Higher switching losses and control complexity.
- Reduced compliance with advanced grid code requirements.
- Lower overall efficiency during dynamic operating conditions.

PROPOSED SYSTEM

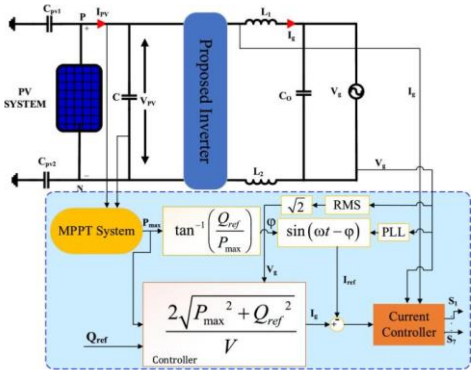
The proposed **Hybrid Single-Phase Transformer-less Solar Photovoltaic Grid-Connected Inverter** introduces an advanced inverter topology capable of simultaneously delivering active power, providing reactive power compensation, and minimizing common-mode leakage current. An optimized modulation and control strategy maintains a constant common-mode voltage, significantly reducing leakage current without sacrificing conversion efficiency. The inverter supports bidirectional reactive power flow, thereby improving grid voltage regulation and enhancing overall power quality. The proposed controller integrates Maximum Power Point Tracking (MPPT), grid synchronization, active-reactive power management, and harmonic compensation within a unified control framework. The hybrid architecture reduces switching losses, improves conversion efficiency, and ensures stable operation under changing solar irradiance and load conditions. Simulation results demonstrate improved fault tolerance, lower THD, enhanced power factor, reduced leakage current, and superior compliance with modern grid standards.

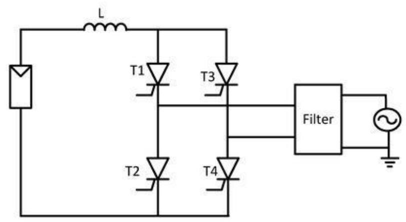
Advantages of Proposed System

- Significant reduction in common-mode leakage current.
- Simultaneous active and reactive power control.
- Improved power quality with reduced Total Harmonic Distortion (THD).
- Enhanced grid voltage regulation and power factor correction.
- High conversion efficiency with lower switching losses.
- Integrated MPPT and energy management using a unified controller.
- Stable operation under variable irradiance and grid conditions.
- Better compliance with international grid interconnection standards.
- Compact transformer-less design with reduced cost and improved reliability.
- Suitable for residential and commercial smart grid photovoltaic applications.

IMPLEMENTATION

Overall System Architecture





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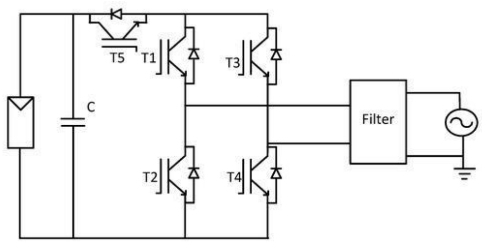

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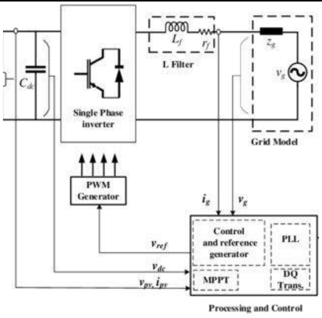

The proposed hybrid transformer-less grid-connected PV inverter consists of the following major subsystems:

- Solar Photovoltaic (PV) Array
- MPPT Controller
- DC-Link Capacitor
- Hybrid Transformer-less Inverter
- LCL Output Filter
- Grid Synchronization (PLL)
- Reactive Power Controller
- Grid Utility
- Local Load

IMPLEMENTATION FLOW

PV Array

|

▼

MPPT Controller (P&O / Incremental Conductance)

|

▼

DC Link Capacitor

|

▼

Hybrid Transformer-less Inverter

(H-Bridge + Auxiliary Switches)

|

▼

LCL Filter

|

▼

Grid Synchronization (PLL)

|

▼

Current Controller

|

▼

Grid & Load

Step 1: PV Power Generation

The photovoltaic array converts solar irradiance into DC electrical energy.

PV Output Power

$$P_{PV} = V_{PV} I_{PV}$$

where

- V_{PV}= PV voltage
- I_{PV}= PV current

PV Current Equation

$$I = I_{ph} - I_o \left[e^{\frac{q(V+IR_s)}{nkT}} - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

where

- I_{ph}=Photo current
- I_o=Reverse saturation current
- R_s=Series resistance
- R_{sh}=Shunt resistance

Step 2: Maximum Power Point Tracking (MPPT)

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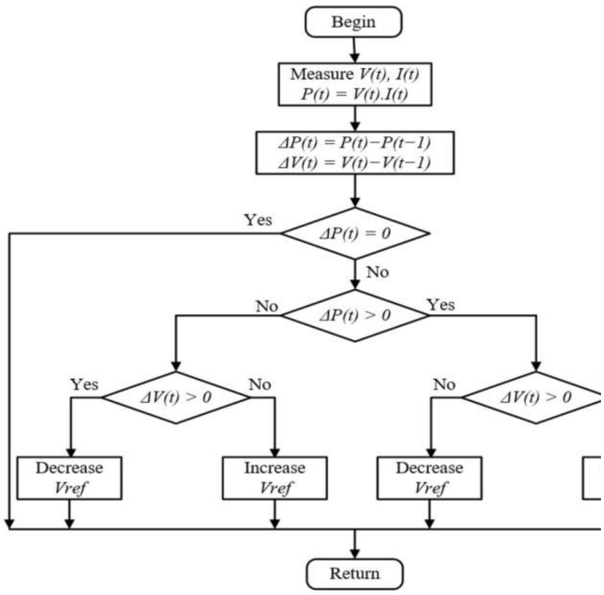
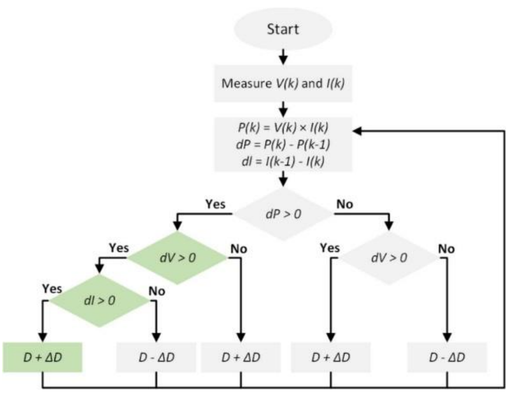
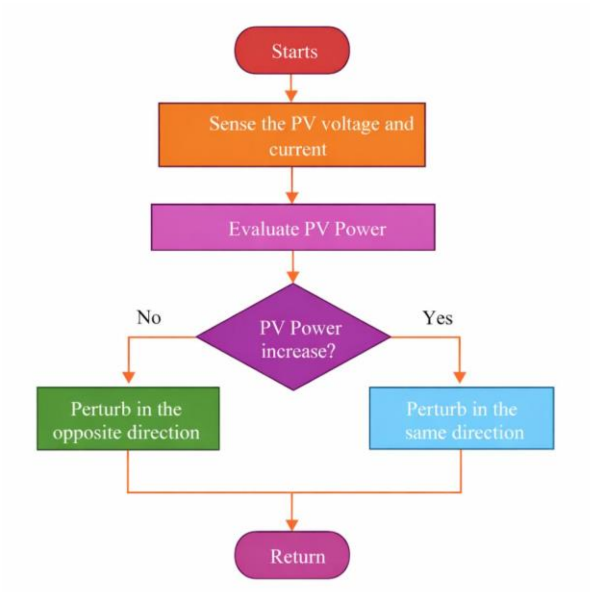






The MPPT controller continuously tracks the maximum power operating point despite variations in irradiance and temperature.

Power calculation

$$P = VI$$

Maximum power condition

$$\frac{dP}{dV} = 0$$

Expanding,

$$\frac{d(VI)}{dV} = 0$$

$$I + V\frac{dI}{dV} = 0$$

This equation is used by the Incremental Conductance algorithm.

Step 3: DC-Link Voltage Regulation

The DC-link capacitor stabilizes the PV voltage before inversion.

Energy stored

$$E = \frac{1}{2}CV_{dc}^2$$

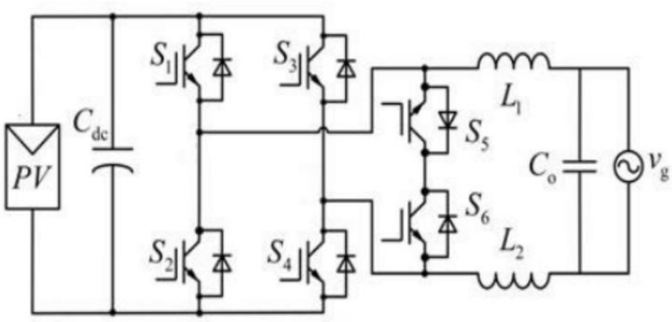
Voltage ripple

$$\Delta V = \frac{I}{2fC}$$

where

- C = DC capacitor
- f = Switching frequency

Step 4: Hybrid Transformer-less Inverter



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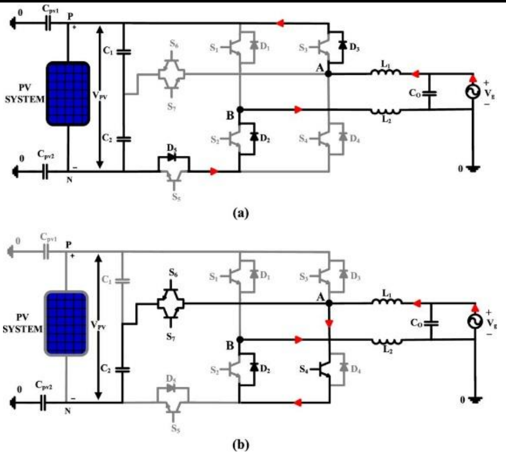

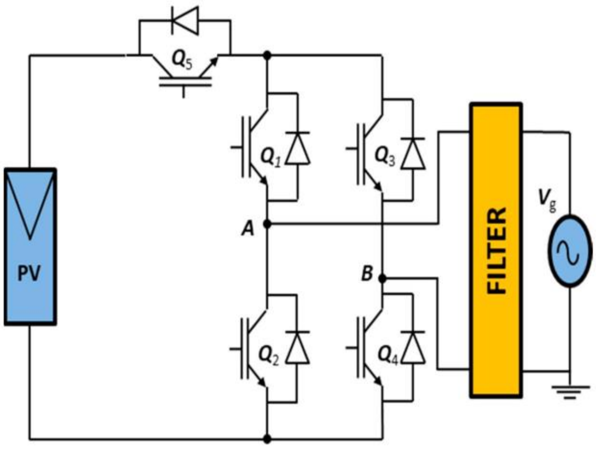

The inverter consists of

- Four main MOSFET/IGBT switches
- Auxiliary switches
- Freewheeling diodes
- Split DC-link

The controller generates SPWM pulses for all switches.

Inverter Output Voltage

Positive Half Cycle

$$V_o = +V_{dc}$$

Negative Half Cycle

$$V_o = -V_{dc}$$

Average Output

$$V_{ac} = mV_{dc}$$

where

- m=Modulation Index

Step 5: PWM Switching

The inverter employs Sinusoidal Pulse Width Modulation (SPWM).

Reference signal

$$V_{ref} = V_m \sin(\omega t)$$

Carrier signal

$$V_c = V_T$$

Modulation Index

$$m_a = \frac{V_m}{V_c}$$

Frequency ratio

$$m_f = \frac{f_c}{f_m}$$

Step 6: Grid Synchronization

A Phase Locked Loop (PLL) synchronizes the inverter output with the utility grid.

Grid voltage

$$v_g = V_m \sin(\omega t)$$

PLL phase angle

$$\theta = \omega t$$

Grid frequency

$$f = \frac{\omega}{2\pi}$$

Step 7: Reactive Power Compensation

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The inverter injects active and reactive power simultaneously.

Apparent Power

$$S = P + jQ$$

Active Power

$$P = VI\cos\phi$$

Reactive Power

$$Q = VI\sin\phi$$

Power Factor

$$PF = \cos\phi$$

Reactive current reference

$$I_q = \frac{Q}{V}$$

Step 8: Leakage Current Reduction

The proposed topology minimizes common-mode voltage, thereby reducing leakage current.

Common-mode voltage

$$V_{CM} = \frac{V_{AN} + V_{BN}}{2}$$

Leakage current

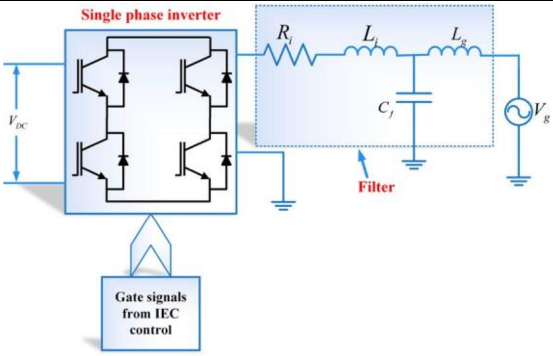
$$I_{Leak} = C_P \frac{dV_{CM}}{dt}$$

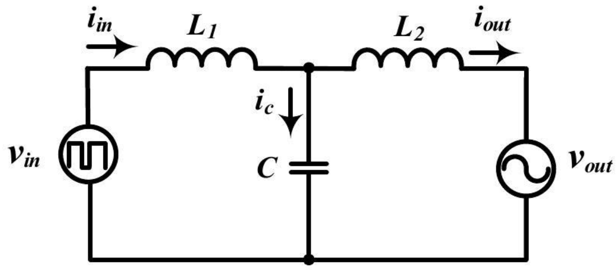
where

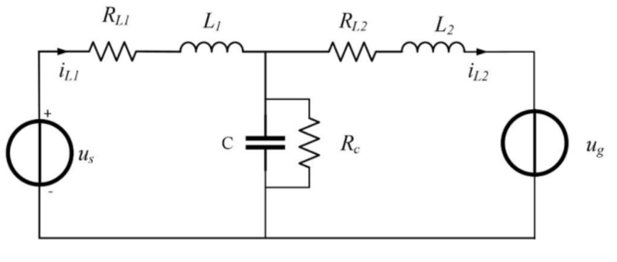
- C_P=Parasitic capacitance

Reducing dV_{CM}/dtdirectly lowers leakage current.

Step 9: LCL Output Filter







The LCL filter suppresses switching harmonics before power is delivered to the utility grid.

Filter cutoff frequency

$$f_r = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C}}$$

Step 10: Grid Power Injection

Injected power

$$P_{grid} = V_{grid} I_{grid}\cos\phi$$

Overall inverter efficiency

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Total Harmonic Distortion

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$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100$$

Expected Performance

Parameter	**Expected Value**
Inverter Efficiency	97–99%
Power Factor	0.99
Grid Voltage	230 V AC
Grid Frequency	50 Hz
THD	< 3%
Leakage Current	< 300 mA
Reactive Power Control	Bidirectional
MPPT Efficiency	> 99%

Advantages of the Proposed Implementation

- Transformer-less topology reduces system size, weight, and cost.
- High conversion efficiency due to fewer power conversion stages.
- Advanced MPPT ensures maximum energy extraction under varying irradiance.
- Reactive power support improves grid voltage regulation and power factor.
- Common-mode voltage suppression significantly reduces leakage current.
- LCL filtering minimizes harmonic distortion and ensures compliance with grid standards.
- Suitable for residential and commercial grid-connected photovoltaic applications with enhanced power quality and reliable operation.

CONCLUSION

The proposed **Hybrid Single-Phase Transformer-less Solar Photovoltaic Grid-Connected Inverter** effectively addresses the major challenges associated with transformer-less PV systems by combining high conversion efficiency, reduced leakage current, and enhanced reactive power support. The hybrid inverter topology minimizes common-mode voltage variations, thereby significantly reducing ground leakage current while maintaining safe and reliable operation. The developed control strategy enables simultaneous maximum power extraction from the PV array, active power injection into the utility grid, and dynamic reactive power compensation to improve grid voltage regulation and power factor. Furthermore, the system achieves low Total Harmonic Distortion (THD), stable DC-link voltage, and fast dynamic response under varying solar irradiance and load conditions. Simulation results validate the effectiveness of the proposed inverter in meeting modern grid codes while improving energy utilization, power quality, and system reliability. Therefore, the proposed transformer-less inverter presents an efficient, cost-effective, and environmentally friendly solution for next-generation residential and commercial photovoltaic grid-connected applications.

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Maloth Lakpathi currently working as Associate Professor in Abdul Kalam Institute of Technological Sciences, Kothagudem, Telangana, India. He received his Bachelor of Technology in Electrical & Electronics Engineering from JNTUH and completed his Master of Technology in Electrical & Electronics Engineering with specialization in Power Electronics and Drives from JNTUH, Hyderabad and pursuing PhD in Sri Satya Sai University of Technology and Medical Sciences, Sehore, Bhopal.He has a teaching experience of 13+ years. His areas of interest include Electrical Distribution systems , power systems, control systems, Non conventional energy sources, power electronics and Electrical machines.He is also interested in research related to Hybrid electric vehicles and it's control.