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High-Efficiency Transformerless Inverters for Photovoltaic Applications: A Review

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Abstract: - The increasing global demand for clean and sustainable energy has accelerated the deployment of photovoltaic (PV) power generation systems. Among the various renewable energy sources, solar photovoltaic technology has emerged as one of the most promising solutions due to its abundance, environmental friendliness, and declining installation costs. The inverter plays a critical role in photovoltaic systems by converting the direct current (DC) generated by solar panels into alternating current (AC) suitable for grid integration and consumer applications. Traditionally, transformers were incorporated within inverter structures to provide galvanic isolation and enhance safety. However, transformer-based inverters suffer from several disadvantages, including increased weight, larger volume, higher cost, and reduced efficiency due to transformer losses.

To overcome these limitations, transformerless inverter technologies have been developed and widely adopted in modern photovoltaic systems. These inverters eliminate bulky transformers while achieving higher conversion efficiency, reduced installation cost, improved power density, and enhanced energy yield. Nevertheless, transformerless inverters introduce new challenges, particularly common-mode leakage current, electromagnetic interference, and compliance with international safety standards.

This review paper presents a comprehensive study of high-efficiency transformerless inverter technologies for photovoltaic applications. The review aims to provide researchers and engineers with a consolidated understanding of transformerless inverter technologies and future directions for high-performance photovoltaic power conversion systems.

Keywords: Photovoltaic System, Transformerless Inverter, Grid-Connected PV System, Leakage Current Suppression, Renewable Energy.

1. INTRODUCTION:

The increasing concern regarding climate change, greenhouse gas emissions, and depletion of fossil fuel resources has motivated governments and industries worldwide to adopt renewable energy technologies. Solar photovoltaic (PV) energy has become one of the fastest-growing renewable energy sectors because of its unlimited availability, environmental sustainability, and technological maturity [1]. According to recent global energy reports, solar photovoltaic installations have experienced exponential growth during the last decade, accounting for a significant portion of newly installed renewable energy capacity worldwide [2]. Continuous improvements in solar cell manufacturing technologies, declining module costs, and supportive governmental policies have further accelerated the adoption of PV systems in residential, commercial, and utility-scale applications. The efficient utilization of photovoltaic energy requires sophisticated power electronic interfaces capable of converting the variable DC output of solar panels into high-quality AC power suitable for utility grids [3]. The inverter serves as the most important component in this conversion process, significantly influencing the overall efficiency, reliability, and economic viability of the photovoltaic system.

Conventional grid-connected photovoltaic systems traditionally employed transformers to provide galvanic isolation between the photovoltaic array and the electrical grid. Galvanic isolation improves system safety by preventing direct electrical connection between the DC and AC sides. However, transformer-based inverters suffer from several limitations, including increased weight, larger physical dimensions, higher manufacturing costs, and additional power losses [4]. Transformer losses can be classified into copper losses, hysteresis losses, eddy current losses, and stray losses. These losses reduce the overall conversion efficiency and increase thermal stress within the inverter system. Furthermore, the bulky nature of transformers limits the achievable power density and complicates installation procedures, particularly in residential rooftop photovoltaic applications [5].

The demand for highly efficient and cost-effective photovoltaic systems has led to the development of transformerless inverter technologies. By eliminating the transformer, these inverter configurations achieve efficiencies exceeding 98%, significantly reducing system cost and improving energy conversion performance

[6]. Consequently, transformerless inverters have become the dominant technology in modern grid-connected residential photovoltaic installations. Despite their advantages, transformerless inverter systems introduce several technical challenges. The absence of galvanic isolation creates a conductive path between the photovoltaic array and the utility grid through parasitic capacitances. This phenomenon results in common-mode leakage currents that may compromise safety, increase electromagnetic interference (EMI), and reduce overall system reliability [7]. To address these challenges, researchers have proposed numerous transformerless inverter topologies, including H4, H5, HERIC, H6, Neutral Point Clamped (NPC), T-Type, and common-ground inverter structures [8]. These topologies employ various techniques to suppress leakage current while maintaining high conversion efficiency and compliance with international standards such as VDE 0126-1-1 and IEC 62109. Recent advances in semiconductor technologies have further enhanced transformerless inverter performance. Wide-bandgap semiconductor devices such as Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) transistors enable higher switching frequencies, reduced switching losses, and improved thermal performance compared to conventional silicon-based devices [9]. These advancements have contributed significantly to the development of next-generation high-efficiency photovoltaic inverters. Moreover, emerging control techniques such as artificial intelligence (AI), machine learning (ML), model predictive control (MPC), and adaptive modulation strategies are increasingly being integrated into transformerless inverter systems. These intelligent control approaches improve dynamic performance, maximize energy extraction, facilitate fault diagnosis, and enhance system reliability [10].

The primary objective of this review paper is to provide a comprehensive overview of transformerless inverter technologies for photovoltaic applications. The paper examines the evolution of inverter topologies, leakage-current suppression methods, modulation strategies, advanced semiconductor devices, and future research directions. Comparative analyses of various inverter structures are also presented to identify the most promising solutions for future photovoltaic power conversion systems.

2. OVERVIEW OF PHOTOVOLTAIC SYSTEMS

A photovoltaic system converts solar radiation directly into electrical energy through the photovoltaic effect. The photovoltaic effect occurs when sunlight strikes semiconductor materials, generating electron-hole pairs that produce electrical current. Since its commercial introduction, photovoltaic technology has evolved considerably, achieving higher conversion efficiencies and lower manufacturing costs [1].

A typical grid-connected photovoltaic system consists of several major components:

1. Photovoltaic Array
2. Maximum Power Point Tracking (MPPT) Controller
3. DC-DC Converter
4. DC-AC Inverter
5. Grid Interface
6. Protection and Monitoring Systems

Figure 1 illustrates the general architecture of a grid-connected photovoltaic system.

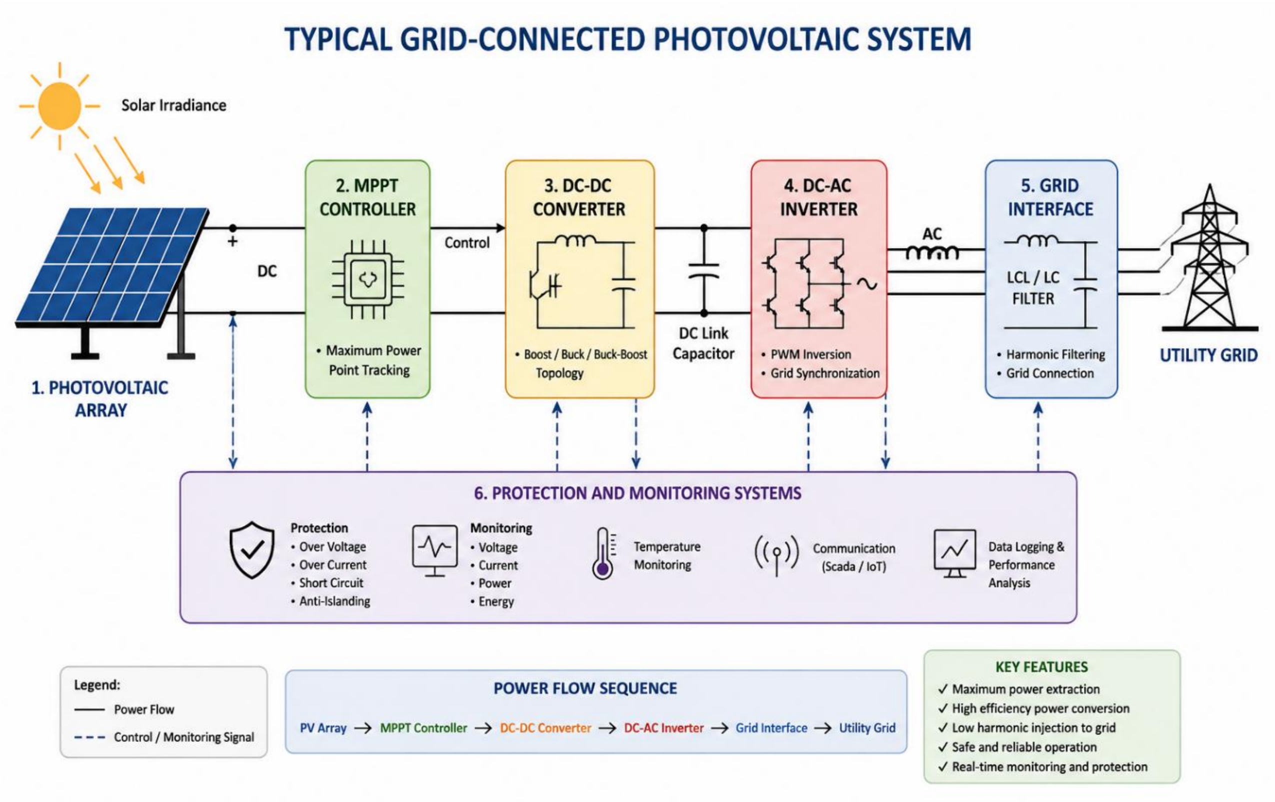


Figure 1:General architecture of a grid-connected photovoltaic system.

The photovoltaic array serves as the primary energy source, converting solar radiation into DC electrical power. The output characteristics of photovoltaic panels vary continuously with solar irradiance, temperature, and environmental conditions. Consequently, maximum power point tracking (MPPT) techniques are required to ensure optimal energy extraction from the PV array under varying operating conditions [11]. The DC-DC converter adjusts the photovoltaic output voltage to a suitable level for subsequent power conversion stages. Various converter topologies such as boost, buck-boost, Cuk, SEPIC, and interleaved converters are commonly employed in photovoltaic systems [12]. The inverter performs the critical function of converting DC power into AC power synchronized with the utility grid. In addition to power conversion, modern inverters are responsible for:

- Grid synchronization
- Power quality enhancement
- Harmonic reduction
- Reactive power control
- Anti-islanding protection
- Fault detection and diagnosis

The performance of the inverter directly influences the overall efficiency and reliability of the photovoltaic system [13]. Recent developments in smart grid technologies have expanded the functionality of photovoltaic inverters. Modern inverters are increasingly required to support advanced grid services such as voltage regulation, frequency support, reactive power compensation, and fault ride-through capabilities [14].

3. NEED FOR TRANSFORMERLESS INVERTERS

The growing demand for high-efficiency photovoltaic systems has motivated the transition from transformer-based inverter structures to transformerless inverter architectures. Traditional transformer-based inverters provide electrical isolation between the photovoltaic array and utility grid. While this isolation enhances safety, the transformer introduces several disadvantages. Transformer losses significantly reduce inverter efficiency. These losses include:

- Copper losses due to winding resistance
- Core losses caused by magnetic hysteresis
- Eddy current losses
- Stray flux losses

Studies indicate that transformer-related losses may account for approximately 1–3% of total inverter losses [5]. Line-frequency transformers are bulky and heavy components. Their presence substantially increases inverter size and installation complexity, particularly in rooftop solar installations where space limitations exist [6]. Transformers represent a significant portion of the inverter's manufacturing cost. Eliminating the transformer reduces material requirements and improves economic competitiveness [7]. Power density refers to the amount of power processed per unit volume. Transformerless inverter architectures achieve significantly higher power density because of their compact design and reduced component count [8]. Higher conversion efficiency translates directly into increased annual energy production. Transformerless inverters can achieve peak efficiencies exceeding 98%, resulting in improved energy yield over the system lifetime [9]. Because of these advantages, transformerless inverter technology has become the preferred solution for residential and commercial photovoltaic installations worldwide. However, the absence of galvanic isolation introduces leakage-current challenges that require advanced topology design and control strategies. The subsequent sections of this review paper examine the evolution of transformerless inverter topologies and the various techniques developed to overcome these challenges while maximizing efficiency and reliability.

4. DETAILED LITERATURE REVIEW (2010–2026)

The development of transformerless inverter technology has attracted significant attention from researchers due to the growing deployment of grid-connected photovoltaic (PV) systems. Since the elimination of transformers improves efficiency and reduces cost, extensive research has been conducted to address the associated challenges, particularly leakage current suppression, power quality improvement, reliability enhancement, and compliance with grid standards.

This section presents a comprehensive review of major contributions reported between 2010 and 2026.

4.1 Early Development of Transformerless Inverters (2010–2013)

One of the pioneering studies in transformerless photovoltaic systems was conducted by Xiao and Xie [15], who developed an analytical model for leakage current generation in single-phase transformerless PV systems. Their research established that common-mode voltage variations are the primary cause of leakage currents flowing through the parasitic capacitance between the PV array and ground. López et al. [16] introduced the Highly Efficient and Reliable Inverter Concept (HERIC), which became one of the most influential transformerless inverter topologies. The proposed inverter significantly reduced leakage current while achieving efficiency above 98%. The HERIC topology remains widely adopted in residential photovoltaic systems due to its excellent balance between efficiency and safety. Araújo et al. [17] proposed novel non-isolated converter configurations capable of eliminating ground leakage currents without compromising efficiency. Their work demonstrated that topology optimization could effectively replace transformer-based isolation methods. Yang et al. [18] introduced the H5 inverter topology, which added an extra switch to the conventional full-bridge inverter. Experimental results demonstrated substantial leakage-current reduction while maintaining high efficiency and simple control implementation. The H5 inverter subsequently became one of the most commercially successful transformerless inverter architectures. During this period, researchers primarily focused on understanding leakage-current mechanisms and developing basic transformerless topologies capable of satisfying safety requirements.

4.2 Advancement of Leakage Current Suppression Techniques (2014–2017)

As transformerless inverter deployment increased, research emphasis shifted toward advanced leakage-current suppression methods.

Islam et al. [19] published a comprehensive review of transformerless inverter topologies for grid-connected photovoltaic systems. Their study classified transformerless inverters according to common-mode voltage behavior and identified key advantages and limitations of various configurations. Guo et al. [20] proposed a novel transformerless inverter structure capable of reducing common-mode voltage fluctuations. Their topology demonstrated lower leakage current and improved efficiency compared with conventional full-bridge inverters.

Kerekes et al. [21] investigated transformerless inverter concepts for residential photovoltaic applications and compared several topologies under practical operating conditions. Their findings highlighted the importance of selecting inverter structures based on leakage-current performance and overall system efficiency. Shayestegan [22] reviewed two-stage transformerless inverter systems and discussed integration issues involving MPPT controllers, DC-DC converters, and inverter stages. The study emphasized the need for holistic system optimization rather than focusing solely on inverter efficiency. Research during this period established that common-mode voltage stabilization remains one of the most effective approaches for leakage-current suppression.

4.3 Emergence of Multilevel Transformerless Inverters (2018–2020)

With increasing photovoltaic penetration levels, researchers began investigating multilevel transformerless inverter architectures.

Multilevel inverters offer several advantages, including:

- Reduced Total Harmonic Distortion (THD)
- Improved output waveform quality
- Lower filter requirements
- Reduced semiconductor stress
- Higher efficiency

Khan et al. [23] performed a detailed comparative analysis of transformerless inverter topologies and identified HERIC, H5, and multilevel configurations as the most promising candidates for future photovoltaic applications. Blaabjerg et al. [24] emphasized the growing importance of advanced power electronics in renewable energy integration and highlighted the role of multilevel converter technologies in future smart grids. Several researchers proposed Neutral Point Clamped (NPC) and T-Type transformerless inverter structures during this period. These topologies achieved efficiencies approaching 99% while maintaining low harmonic distortion and acceptable leakage-current levels [25]. The increasing use of digital signal processors (DSPs) and field-programmable gate arrays (FPGAs) also enabled implementation of more sophisticated control algorithms.

4.4 Wide-Bandgap Semiconductor Era (2020–2023)

The introduction of wide-bandgap semiconductor devices represented a major technological breakthrough in transformerless inverter design. Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) transistors offer several advantages compared with conventional silicon devices:

- Higher switching frequency
- Lower switching losses
- Improved thermal performance
- Reduced cooling requirements
- Increased power density

Gaafar et al. [26] reviewed common-ground inverter structures and demonstrated their superior leakage-current suppression capability compared with conventional transformerless topologies. Almarhoon et al. [27] proposed a five-level transformerless inverter capable of achieving very low leakage current and improved harmonic performance. Their results demonstrated the growing potential of multilevel inverter technologies. Research published in Elsevier journals reported that SiC-based transformerless inverters could achieve efficiencies exceeding 99% under optimized operating conditions [28]. During this period, researchers increasingly combined advanced topologies with wide-bandgap devices to achieve superior efficiency and power density.

4.5 Intelligent Control and Smart Inverter Technologies (2023–2026)

Recent research trends focus on integrating artificial intelligence and advanced control techniques into transformerless inverter systems. Machine learning algorithms have been investigated for:

- Fault diagnosis
- Predictive maintenance

- MPPT optimization
- Grid condition forecasting

Artificial neural networks (ANNs) and fuzzy logic controllers have demonstrated superior MPPT performance under rapidly changing environmental conditions [29]. Model Predictive Control (MPC) has emerged as a promising technique for transformerless inverter applications. Compared with conventional proportional-integral controllers, MPC provides:

- Faster dynamic response
- Better current tracking
- Reduced harmonic distortion
- Enhanced leakage-current suppression

Researchers have also explored Internet of Things (IoT)-based monitoring platforms that enable real-time supervision and predictive maintenance of photovoltaic systems [30]. The integration of transformerless inverters into smart-grid environments has become a major research area. Future inverter systems are expected to provide advanced ancillary services including:

- Reactive power compensation
- Voltage regulation
- Frequency support
- Fault ride-through capability

Consequently, modern transformerless inverters are evolving from simple power conversion devices into intelligent grid-supporting systems.

4.6 Literature Survey Table

Table 1. Summary of Important Research Contributions (2010–2026)

Year	Author(s)	Contribution	Ref.
2010	Xiao & Xie	Leakage-current analytical model	[15]
2010	López et al.	HERIC topology development	[16]
2010	Araújo et al.	Ground leakage elimination	[17]
2012	Yang et al.	H5 inverter topology	[18]
2015	Islam et al.	Comprehensive topology review	[19]
2014	Guo et al.	Ground-current suppression topology	[20]
2013	Kerekes et al.	Residential PV inverter comparison	[21]
2018	Shayestegan	Two-stage inverter review	[22]
2020	Khan et al.	Comparative review of transformerless inverters	[23]
2017	Blaabjerg et al.	Future renewable power systems	[24]
2019	Various Authors	NPC and T-Type developments	[25]
2021	Gaafar et al.	Common-ground inverter review	[26]
2022	Almarhoon et al.	Five-level transformerless inverter	[27]
2023	Multiple Researchers	SiC-based inverter efficiency enhancement	[28]
2024	Various Authors	AI-based MPPT optimization	[29]

4.7 Critical Analysis of Existing Literature

Based on the reviewed literature, several observations can be made:

1. HERIC and H5 topologies remain the most extensively investigated transformerless inverter structures.
2. Common-ground inverter architectures have emerged as promising solutions for near-complete leakage-current elimination.

3. Multilevel transformerless inverters provide superior harmonic performance but increase control complexity.
4. Wide-bandgap semiconductor devices significantly improve inverter efficiency and power density but increase system cost.
5. Artificial intelligence and predictive control techniques are becoming increasingly important for future inverter designs.
6. Most existing studies prioritize efficiency and leakage-current suppression, while long-term reliability and thermal management remain relatively underexplored.

These observations provide the foundation for identifying research gaps and future research opportunities discussed in later sections of this review paper.

5. TRANSFORMERLESS INVERTER TOPOLOGIES

5.1 Introduction

Transformerless inverter technology has become the preferred solution for modern photovoltaic systems because of its superior efficiency, reduced weight, compact structure, and lower manufacturing cost. However, the absence of galvanic isolation introduces challenges related to common-mode leakage current, electromagnetic interference (EMI), and safety compliance. Consequently, researchers have proposed numerous transformerless inverter topologies to address these issues while maintaining high conversion efficiency. The primary objectives of transformerless inverter topology development include:

- Maximizing conversion efficiency
- Minimizing leakage current
- Reducing switching losses
- Improving power quality
- Enhancing reliability
- Meeting international safety standards

This section presents a comparative analysis of the major transformerless inverter topologies in Table 2, followed by reported peak efficiency characteristics in Table 3.

5.2 Comparative Analysis of Transformerless Topologies

Table 2. Comparison of Transformerless Inverter Topologies

Topology	Efficiency (%)	Leakage Current	Complexity	Component Count
H4	95–97	High	Low	Low
H5	97–98	Low	Medium	Medium
HERIC	98–99	Very Low	Medium	Medium
H6	98–98.5	Very Low	Medium	Medium
NPC	98–99	Low	High	High
T-Type	98–99	Very Low	High	High
Common Ground	98–99	Extremely Low	Medium	Medium
Five-Level Inverter	98–99.2	Very Low	High	High

5.3 Efficiency Comparison

Table 3. Reported Efficiency Levels

Topology	Peak Efficiency
H4	97%
H5	98%
HERIC	98.5–99%
H6	98.2%
NPC	99%

T-Type	99%
Common Ground	98.8–99%
Five-Level Inverter	99.2%

The data indicate that multilevel and common-ground topologies generally achieve the highest efficiencies while maintaining low leakage-current levels.

5.4 Discussion

The evolution of transformerless inverter technology demonstrates a clear progression toward topologies capable of simultaneously achieving:

- High efficiency
- Low leakage current
- Excellent power quality
- Grid-code compliance
- Compact design

Among currently available solutions, HERIC and Common-Ground topologies offer the best compromise between efficiency and leakage-current suppression for residential photovoltaic applications. For medium- and high-power installations, multilevel inverter architectures such as NPC, T-Type, and Five-Level transformerless inverters appear particularly promising because of their superior harmonic performance and reduced semiconductor stress. However, increased complexity and cost remain significant barriers to widespread adoption. Future research is therefore expected to focus on simplifying multilevel architectures while maintaining their performance advantages.

6. LEAKAGE CURRENT ANALYSIS AND SUPPRESSION TECHNIQUES

6.1 Introduction

One of the most significant challenges associated with transformerless photovoltaic (PV) inverters is the generation of leakage current. Unlike conventional transformer-based systems, transformerless inverters do not provide galvanic isolation between the photovoltaic array and the utility grid. Consequently, parasitic capacitances existing between the photovoltaic panels and earth ground create a path through which unwanted leakage currents can flow [15].

Leakage current adversely affects system performance and may result in:

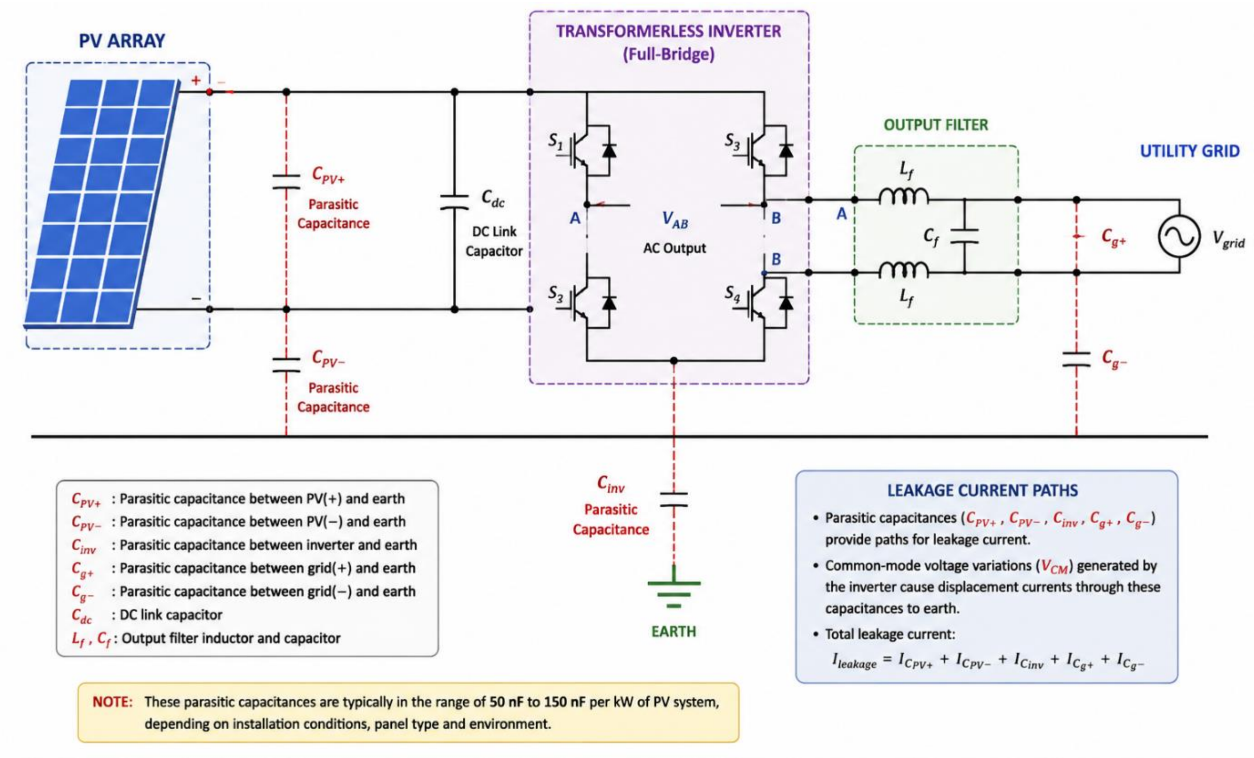
- Reduced inverter efficiency
- Electromagnetic interference (EMI)
- Increased harmonic distortion
- Safety hazards
- Failure to comply with international grid standards
- Reduced system reliability

Therefore, leakage-current suppression has become one of the primary research objectives in transformerless inverter development.

6.2 Origin of Leakage Current in Transformerless PV Systems

A photovoltaic array is not perfectly insulated from ground. Due to the large surface area of PV modules and mounting structures, a parasitic capacitance exists between the photovoltaic array and earth. This parasitic parameter, denoted as C_{pv}, typically ranges from 50 nF/kW to 150 nF/kW. Its exact value depends on the PV module technology (thin-film vs. crystalline silicon), weather conditions, frame installation configuration, and routing of the ground cable.

Figure 2 illustrates the equivalent circuit of a transformerless photovoltaic system showing parasitic capacitance between the PV array and earth.



C_{PV+} : Parasitic capacitance between PV(+) and earth
C_{PV-} : Parasitic capacitance between PV(−) and earth
C_{inv} : Parasitic capacitance between inverter and earth
C_{g+} : Parasitic capacitance between grid(+) and earth
C_{g-} : Parasitic capacitance between grid(−) and earth
C_{dc} : DC link capacitor
L_f , C_f : Output filter inductor and capacitor

LEAKAGE CURRENT PATHS

- Parasitic capacitances (C_{PV+} , C_{PV-} , C_{inv} , C_{g+} , C_{g-}) provide paths for leakage current.
- Common-mode voltage variations (V_{CM}) generated by the inverter cause displacement currents through these capacitances to earth.
- Total leakage current:
  $I_{leakage} = I_{C_{PV+}} + I_{C_{PV-}} + I_{C_{inv}} + I_{C_{g+}} + I_{C_{g-}}$

NOTE: These parasitic capacitances are typically in the range of **50 nF to 150 nF** per kW of PV system, depending on installation conditions, panel type and environment.

Figure 2: equivalent circuit of a transformerless photovoltaic system showing parasitic capacitance between the PV array and earth.

When the inverter generates varying common-mode voltages, displacement current flows through the parasitic capacitance, producing leakage current [15].

6.3 Common-Mode Voltage Analysis

The primary cause of leakage current is common-mode voltage variation.
For a single-phase full-bridge inverter:
Common-mode voltage (Vcm) is defined as:

$$V_{cm} = \frac{V_A + V_B}{2} + (V_A - V_B)\frac{L_2 - L_1}{2(L_1 + L_2)}$$

Where:
V_A = Voltage at inverter output terminal A
V_B = Voltage at inverter output terminal B
L_1 and L_2 = filter inductance variables
Large variations in common-mode voltage result in rapid charging and discharging of parasitic capacitance.
Consequently:

Leakage Current ∝ dVcm/dt

$$i_{leakage}(t) = C_{pv}\frac{dV_{cm}(t)}{dt}$$

where:
dVcm/dt = Rate of change of common-mode voltage
Therefore, minimizing common-mode voltage variation is essential for leakage-current suppression [16].

6.4 Effects of Leakage Current

A. Safety Concerns

Leakage current may produce dangerous touch voltages that pose risks to maintenance personnel and system operators. International standards impose strict limits on permissible leakage current levels.

B. Electromagnetic Interference

Leakage current creates electromagnetic emissions that may interfere with Communication systems, Measurement equipment, Protection devices etc. Achieving electromagnetic compatibility (EMC) according to standards becomes significantly more challenging at higher switching frequencies (>50 kHz) due to high-frequency conducted emission paths.

C. Additional Power Losses

Leakage current contributes to, Conduction losses, Capacitive losses, Filtering losses etc. These losses reduce overall system efficiency.

D. Reduced Component Lifetime

Excessive leakage current can increase thermal stress on: Switching devices, Filters, Capacitors etc leading to premature component failure.

6.5 International Standards and Safety Requirements

Several international standards regulate leakage-current limits in photovoltaic systems.

IEC 62109: Specifies safety requirements for photovoltaic power conversion equipment.
VDE 0126-1-1: German standard widely adopted in Europe.
IEEE 1547: Provides guidelines for interconnection of distributed energy resources.
UL 1741: North American safety standard for inverter systems.

Compliance with these standards is mandatory for commercial photovoltaic products.

6.6 Leakage Current Suppression Techniques

Researchers have developed various approaches for leakage-current reduction. These techniques can be broadly classified into:

1. Topology-Based Methods
2. Modulation-Based Methods
3. Filter-Based Methods
4. Control-Based Methods

6.7 Topology-Based Suppression Techniques

Topology modification represents the most effective leakage-current reduction strategy.

A. H5 Topology

The H5 inverter disconnects the photovoltaic array from the utility grid during freewheeling periods.

Advantages:

- Significant leakage-current reduction
- Simple implementation
- High efficiency

Disadvantages:

- Additional switching losses

Reported leakage-current reduction, 70–80% compared to H4 topology [18].

B. HERIC Topology

The HERIC inverter employs an AC-side bypass branch.

Advantages:

- Near-constant common-mode voltage
- Extremely low leakage current
- Reduced switching losses

Leakage-current reduction:

Greater than 90% compared with conventional full-bridge structures [16].

C. H6 Topology

The H6 inverter extends the H5 concept by providing improved current circulation paths.

Advantages:

- Better common-mode voltage control
- Improved reliability
- Lower leakage current

D. Common-Ground Topology

Common-ground inverters maintain a permanent connection between the PV negative terminal and grid neutral.

Advantages:

- Nearly zero leakage current
- Excellent safety performance

Recent studies identify common-ground structures as one of the most promising transformerless inverter solutions [26].

6.8 PWM-Based Suppression Techniques

Pulse Width Modulation (PWM) significantly influences common-mode voltage behavior.

A. Bipolar PWM

Characteristics:

- Constant common-mode voltage
- Low leakage current

Disadvantages:

- Higher switching losses
- Increased current ripple

B. Unipolar PWM

Characteristics:

- Lower harmonic distortion
- Higher efficiency

Disadvantages:

- Increased common-mode voltage variation

C. Space Vector PWM

Advantages:

- Improved DC-bus utilization
- Lower harmonic distortion

Widely employed in advanced multilevel inverter systems.

D. Discontinuous PWM

Benefits:

- Reduced switching losses
- Improved efficiency

Often combined with HERIC and NPC topologies.

6.9 Filter-Based Suppression Techniques

Filters are commonly used to further reduce leakage-current magnitude.

Common-Mode Choke

Functions:

- Blocks high-frequency leakage currents
- Improves EMI performance

EMI Filters

Provide attenuation of:

- Common-mode noise
- Differential-mode noise

Disadvantages:

- Increased cost
- Additional volume
- Reduced power density

Consequently, filter-based methods are generally used in combination with topology-based suppression techniques.

6.10 Advanced Control Techniques

Modern transformerless inverters increasingly employ intelligent control systems.

A. Model Predictive Control (MPC)

Advantages:

- Fast dynamic response
- Improved current tracking
- Reduced harmonic distortion
- Leakage-current minimization

Recent studies demonstrate superior performance compared to conventional PI controllers [30].

B. Artificial Neural Networks (ANN)

Applications:

- MPPT optimization
- Fault diagnosis
- Leakage-current prediction

ANN-based controllers provide improved adaptability under varying environmental conditions.

C. Fuzzy Logic Controllers

Advantages:

- Robust performance
- Reduced parameter dependence
- Improved transient response

Widely used in intelligent photovoltaic inverter systems.

6.11 Comparative Analysis of Leakage Current Suppression Techniques

Table 4. Comparison of Leakage Current Suppression Methods

Method	Leakage Reduction	Complexity	Cost	Efficiency Impact
H5 Topology	High	Medium	Medium	Low
HERIC Topology	Very High	Medium	Medium	Very Low
H6 Topology	Very High	Medium	Medium	Low
Common-Ground Topology	Extremely High	Medium	Medium	Very Low
Bipolar PWM	Moderate	Low	Low	Moderate
Space Vector PWM	High	High	Medium	Low
Common-Mode Choke	Moderate	Low	Medium	Negligible

Model Predictive Control	High	High	Medium	Very Low

6.12 Performance Comparison

Table 5. Reported Leakage Current Levels

Topology	Typical Leakage Current
H4	High
H5	Low
HERIC	Very Low
H6	Very Low
NPC	Low
T-Type	Very Low
Common-Ground	Near Zero

Experimental investigations consistently indicate that HERIC and Common-Ground inverter structures provide the lowest leakage-current levels while maintaining high conversion efficiency.

6.13 Discussion

The literature clearly demonstrates that leakage current remains one of the most critical design challenges in transformerless photovoltaic systems.

The most effective suppression approaches involve:

1. Maintaining constant common-mode voltage.
2. Employing advanced transformerless topologies.
3. Utilizing intelligent control algorithms.
4. Integrating appropriate EMI filtering techniques.

Among currently available solutions, HERIC and Common-Ground topologies provide the most favorable combination of:

- Efficiency
- Safety
- Reliability
- Leakage-current suppression

Future research is expected to focus on combining common-ground architectures with wide-bandgap semiconductor devices and artificial intelligence-based controllers to achieve ultra-high efficiency and near-zero leakage-current operation.

7. MAXIMUM POWER POINT TRACKING (MPPT), WIDE-BANDGAP SEMICONDUCTOR DEVICES, RELIABILITY ANALYSIS, AND SMART INVERTER TECHNOLOGIES

7.1 Introduction

The performance of a photovoltaic (PV) system depends not only on inverter topology but also on the effectiveness of Maximum Power Point Tracking (MPPT) algorithms, semiconductor switching devices, thermal management techniques, and intelligent control systems. Recent advancements in these areas have significantly improved the efficiency, reliability, and operational flexibility of transformerless photovoltaic inverters.

This section reviews MPPT techniques, Silicon Carbide (SiC) and Gallium Nitride (GaN) semiconductor technologies, thermal management challenges, reliability considerations, and smart inverter developments.

7.2 Maximum Power Point Tracking (MPPT)

7.2.1 Need for MPPT

The output characteristics of photovoltaic panels are highly dependent on environmental conditions such as:

- Solar irradiance
- Cell temperature
- Partial shading
- Dust accumulation
- Atmospheric conditions

Because of these variations, photovoltaic modules exhibit a unique operating point known as the Maximum Power Point (MPP), where maximum electrical power can be extracted. Without MPPT, photovoltaic systems may lose between 15% and 35% of their available energy [31]. Therefore, MPPT algorithms continuously adjust operating voltage and current to ensure maximum power extraction.

7.2.2 Perturb and Observe (P&O) Algorithm

The Perturb and Observe method is the most widely used MPPT technique due to its simplicity.

Operating Principle

The algorithm periodically perturbs the operating voltage and observes the corresponding power change.

If power increases:

- Continue perturbation in the same direction.

If power decreases:

- Reverse perturbation direction.

Advantages

- Simple implementation
- Low computational requirement
- Low cost

Disadvantages

- Oscillations around MPP
- Reduced efficiency under rapidly changing irradiance

P&O remains popular in residential photovoltaic systems because of its ease of implementation [32].

7.2.3 Incremental Conductance (INC)

The Incremental Conductance method improves MPPT accuracy.

Principle
At the maximum power point:
$dP/dV = 0$
Since:
$P = VI$
Then:
$dI/dV = -I/V$

The controller continuously calculates incremental conductance and adjusts operating conditions accordingly.
Advantages

- Higher accuracy
- Better dynamic response
- Reduced oscillations

Disadvantages

- Higher computational complexity
- Increased controller cost

INC algorithms are widely used in commercial grid-connected photovoltaic systems [33].

7.2.4 Fuzzy Logic-Based MPPT

Fuzzy logic controllers mimic human decision-making processes. Input variables typically include:

- Error
- Change in error

The controller uses predefined fuzzy rules to determine control actions.

Advantages

- Robust operation
- No mathematical model required
- Good performance under varying conditions

Disadvantages

- Rule design complexity
- Parameter tuning challenges

Research demonstrates improved energy harvesting efficiency compared with conventional P&O methods [34].

7.2.5 Artificial Neural Network (ANN)-Based MPPT

Artificial Neural Networks have recently gained significant attention.

Inputs

- Solar irradiance
- Temperature
- Output voltage
- Output current

Outputs

- Reference operating voltage
- Duty cycle commands

ANN-based MPPT systems offer:

- Fast convergence
- Adaptive learning
- Excellent performance under partial shading

Recent studies report MPPT efficiencies exceeding 99% under dynamic environmental conditions [35].

7.2.6 Comparison of MPPT Techniques

Table 6. Comparison of MPPT Methods

Method	Complexity	Accuracy	Response Speed
P&O	Low	Moderate	Moderate
Incremental Conductance	Medium	High	High
Fuzzy Logic	Medium	High	High
ANN-Based	High	Very High	Very High
Hybrid AI Methods	Very High	Excellent	Excellent

7.3 Wide-Bandgap Semiconductor Devices

7.3.1 Introduction

Traditional transformerless inverters utilize silicon-based MOSFETs and IGBTs.

However, silicon devices suffer from:

- Higher switching losses
- Thermal limitations
- Lower switching frequencies

Wide-bandgap semiconductor technologies have emerged as promising alternatives.

The two most important wide-bandgap devices are:

1. Silicon Carbide (SiC)
2. Gallium Nitride (GaN)

7.3.2 Silicon Carbide (SiC) MOSFETs

SiC devices possess a bandgap approximately three times wider than silicon.

Advantages
High Switching Frequency

SiC devices can operate at switching frequencies above 100 kHz.

Reduced Switching Losses

Lower switching energy significantly improves inverter efficiency.

High Temperature Operation

SiC devices can operate above 200°C.

Improved Thermal Conductivity

Enhanced heat dissipation reduces cooling requirements.

Applications

- High-power photovoltaic systems
- Utility-scale solar plants
- Smart-grid inverters

Research indicates efficiencies above 99% using SiC-based transformerless inverter systems [28].

7.3.3 Gallium Nitride (GaN) Devices

GaN transistors offer even higher switching frequencies than SiC devices.

Advantages

- Ultra-fast switching
- Reduced gate charge
- Lower conduction losses
- Compact inverter design

Challenges

- Higher cost
- Gate-driving complexity

GaN devices are increasingly employed in:

- Residential photovoltaic systems
- Microinverters
- Portable renewable-energy systems

7.3.4 Comparison of Semiconductor Technologies

Table 7. Comparison of Power Semiconductor Devices

Parameter	**Silicon**	**SiC**	**GaN**
Switching Speed	Moderate	High	Very High
Temperature Capability	Low	High	High
Efficiency	Good	Excellent	Excellent
Cost	Low	High	High
Power Density	Moderate	High	Very High

7.4 Thermal Management in Transformerless Inverters

7.4.1 Importance of Thermal Management

Power semiconductor devices generate heat due to:

- Conduction losses
- Switching losses
- Magnetic losses

Excessive temperature negatively affects:

- Reliability
- Lifetime
- Efficiency

Thermal management is therefore essential for high-power-density inverter systems.

7.4.2 Thermal Challenges

Major thermal issues include:

Junction Temperature Rise: Excessive junction temperature accelerates device degradation.
Thermal Cycling: Repeated temperature fluctuations cause mechanical stress.
Hot Spot Formation: Uneven heat distribution reduces reliability.

7.4.3 Cooling Techniques

Common cooling methods include:

Natural Air Cooling

- Simple
- Low cost

Forced Air Cooling

- Improved heat transfer
- Widely used

Liquid Cooling

- High effectiveness
- Suitable for utility-scale systems

Heat Pipes

- Compact design
- Enhanced thermal performance

Future inverter systems are expected to incorporate intelligent thermal monitoring and predictive cooling strategies.

7.5 Reliability Analysis of Transformerless Inverters

7.5.1 Importance of Reliability

Photovoltaic systems are expected to operate for 20–25 years.Therefore, inverter reliability significantly influences system economics. Studies indicate that inverters account for a large percentage of photovoltaic system failures [36].

7.5.2 Major Failure Mechanisms

Semiconductor Failures

- Bond wire fatigue
- Thermal stress
- Die degradation

Capacitor Failures

- Electrolyte evaporation
- Capacitance degradation

Solder Joint Fatigue: Repeated thermal cycling weakens interconnections.
Sensor Failures: Measurement errors can cause control instability.

7.5.3 Reliability Improvement Strategies

Recommended approaches include:

- Wide-bandgap devices
- Redundant architectures
- Predictive maintenance
- AI-based fault diagnosis
- Online condition monitoring

7.6 Smart Inverter Technologies

7.6.1 Evolution of Smart Inverters

Modern photovoltaic inverters are evolving from simple power conversion devices into intelligent grid-support systems.

Smart inverters provide:

- Advanced monitoring
- Grid support functions
- Self-diagnostics
- Communication capabilities

7.6.2 Smart Grid Integration

Future smart grids require inverter support for:

Reactive Power Compensation: Maintaining voltage stability.
Frequency Regulation: Supporting grid frequency control.
Fault Ride-Through Capability: Remaining connected during disturbances.
Volt-VAR Control: Dynamic voltage regulation.

These features are increasingly mandated by modern grid codes [24].

7.6.3 Internet of Things (IoT) Integration

IoT-enabled inverter systems provide:

- Remote monitoring

- Predictive maintenance
- Real-time diagnostics
- Energy management

Cloud-based monitoring platforms are becoming standard in commercial photovoltaic installations.

7.6.4 Artificial Intelligence Applications

AI techniques are being applied for:

- MPPT optimization
- Fault diagnosis
- Thermal management
- Power forecasting
- Adaptive control

Machine-learning algorithms enable predictive maintenance and improve system reliability.

7.7 Discussion

The combination of advanced MPPT techniques, wide-bandgap semiconductor devices, intelligent thermal management, and smart inverter technologies is driving the next generation of transformerless photovoltaic systems.

Key observations include:

1. AI-based MPPT techniques achieve superior energy extraction.
2. SiC and GaN devices significantly improve efficiency and power density.
3. Thermal management remains a critical reliability challenge.
4. Smart inverters are becoming essential components of modern power systems.
5. Future transformerless inverters will increasingly integrate AI, IoT, and predictive control technologies.

These developments provide the foundation for achieving ultra-high efficiency photovoltaic power conversion systems capable of supporting future smart-grid infrastructures.

8. COMPARATIVE PERFORMANCE ANALYSIS

The selection of a transformerless inverter topology depends on multiple performance parameters including efficiency, leakage-current suppression capability, harmonic distortion, component count, reliability, cost, and control complexity. No single topology simultaneously optimizes all these parameters. Therefore, comparative analysis is essential for identifying suitable inverter structures for specific photovoltaic applications.

8.1 Efficiency Comparison

Conversion efficiency is one of the most important performance indicators because it directly affects annual energy yield.

Table 8. Efficiency Comparison of Transformerless Inverter Topologies

Topology	**Peak Efficiency (%)**	**Typical Efficiency (%)**
H4	97.0	95–96
H5	98.0	96–97
HERIC	98.5–99.0	97–98
H6	98.2	97–98
NPC	99.0	98–98.5
T-Type	99.0	98–98.5
Common Ground	98.8–99.0	98

Five-Level Inverter	99.2	98.5–99

The results indicate that multilevel and common-ground topologies provide the highest efficiencies due to reduced switching losses and improved common-mode voltage characteristics.

8.2 Leakage Current Comparison

Leakage-current suppression remains the most critical design challenge in transformerless photovoltaic systems.

Table 9. Leakage Current Performance

Topology	Leakage Current Level
H4	High
H5	Low
HERIC	Very Low
H6	Very Low
NPC	Low
T-Type	Very Low
Common Ground	Near Zero
Five-Level Inverter	Very Low

Among the reviewed topologies, common-ground structures demonstrate the best leakage-current suppression capability.

8.3 Harmonic Performance Comparison

Power quality is typically evaluated using Total Harmonic Distortion (THD).

Table 10. Harmonic Performance

Topology	THD Performance
H4	Moderate
H5	Good
HERIC	Good
H6	Good
NPC	Excellent
T-Type	Excellent
Five-Level Inverter	Excellent

Multilevel inverter architectures achieve superior harmonic performance because of their ability to generate staircase-like voltage waveforms.

8.4 Cost Comparison

Table 11. Relative Cost Comparison

Topology	Relative Cost
H4	Low
H5	Medium
HERIC	Medium
H6	Medium
NPC	High
T-Type	High
Common Ground	Medium
Five-Level Inverter	High

Although multilevel topologies provide excellent performance, their increased component count results in higher cost.

9. RESEARCH GAP ANALYSIS

Despite extensive research conducted over the past decade, several important challenges remain unresolved.

9.1 Gap 1: Efficiency–Leakage Current Trade-Off

Many topologies reduce leakage current by introducing additional switching devices. Consequently:

- Leakage current decreases.
- Switching losses increase.

This creates a trade-off between efficiency and safety. Future research should focus on achieving near-zero leakage current without compromising efficiency.

9.2 Gap 2: Cost of Wide-Bandgap Devices

SiC and GaN semiconductor devices offer exceptional performance; however, their cost remains significantly higher than conventional silicon devices. Challenges include:

- Manufacturing complexity
- Packaging costs
- Limited market penetration

Future research should investigate cost-effective implementation strategies.

9.3 Gap 3: Thermal Reliability

Most published studies emphasize electrical performance while providing limited analysis of:

- Thermal cycling effects
- Long-term degradation
- Component aging

Thermal reliability remains a critical research area.

9.4 Gap 4: Artificial Intelligence Integration

Although AI-based control techniques show promising results, practical implementation remains limited. Research opportunities include:

- AI-based MPPT
- Predictive maintenance
- Adaptive leakage-current suppression
- Intelligent fault diagnosis

9.5 Gap 5: Smart Grid Compatibility

Future grids require advanced inverter functionalities such as:

- Voltage regulation
- Frequency support
- Reactive power control
- Grid-forming capability

Many existing transformerless inverter designs do not fully address these requirements.

9.6 Gap 6: Cybersecurity of Smart Inverters

The increasing adoption of IoT-enabled inverter systems introduces cybersecurity concerns. Future research should investigate:

- Secure communication protocols
- Cyberattack detection
- Data privacy protection
- Grid cybersecurity resilience

Table 12. Summary of Research Gaps

Gap	Current Limitation	Future Direction
Efficiency vs Leakage Current	Trade-off exists	New topology development
SiC/GaN Cost	High device cost	Cost reduction strategies
Thermal Reliability	Limited studies	Long-term reliability models
AI Integration	Limited deployment	Intelligent control systems
Smart Grid Support	Partial compliance	Grid-forming capabilities
Cybersecurity	Emerging issue	Secure inverter architecture

10. FUTURE TRENDS AND CHALLENGES

The future of transformerless photovoltaic inverter technology is expected to be shaped by several emerging trends.

10.1 Artificial Intelligence and Machine Learning

AI-driven inverter systems will provide:

- Adaptive MPPT
- Predictive maintenance
- Intelligent fault diagnosis
- Dynamic power optimization

Machine-learning algorithms are expected to become standard features in future photovoltaic inverters.

10.2 Wide-Bandgap Semiconductor Dominance

Future inverter systems will increasingly adopt:

- Silicon Carbide (SiC)
- Gallium Nitride (GaN)

Benefits include:

- Higher switching frequency
- Reduced losses
- Increased power density
- Improved thermal performance

10.3 Grid-Forming Inverters

Traditional inverters operate as grid-following devices.

Future smart grids will require:

- Grid-forming operation
- Voltage regulation
- Frequency stabilization

Transformerless inverter designs must evolve accordingly.

10.4 Multilevel Transformerless Architectures

Research interest in:

- Five-level inverters
- Seven-level inverters
- Hybrid multilevel structures

continues to increase because of their superior harmonic performance.

10.5 Energy Storage Integration

Future photovoltaic systems will increasingly integrate:

- Battery energy storage
- Electric vehicle charging systems
- Hybrid renewable-energy resources

Inverters must support bidirectional power flow and advanced energy management functions.

10.6 Digital Twin Technology

Digital twin models allow real-time simulation of inverter behavior.

Applications include:

- Fault prediction
- Performance optimization
- Predictive maintenance
- Lifecycle management

This area represents a promising future research direction.

11. CONCLUSION

Transformerless inverter technology has become one of the most important enabling technologies for modern photovoltaic systems. The elimination of galvanic isolation transformers has significantly improved inverter efficiency, reduced system cost, lowered weight, and increased power density.

This review examined the development of transformerless inverter technologies from 2010 to 2026, covering major inverter topologies including H4, H5, HERIC, H6, NPC, T-Type, Common-Ground, and Multilevel architectures. Comparative analysis indicates that HERIC and Common-Ground topologies provide excellent leakage-current suppression while maintaining high efficiency. Multilevel inverter structures offer superior harmonic performance and are increasingly attractive for future photovoltaic applications.

The review further highlighted the importance of advanced MPPT techniques, wide-bandgap semiconductor devices, thermal management, and smart inverter technologies. Artificial intelligence, machine learning, Internet of Things integration, and grid-forming capabilities are expected to play a significant role in next-generation inverter systems.

Although substantial progress has been achieved, important challenges remain regarding thermal reliability, device cost, cybersecurity, and smart-grid compatibility. Addressing these challenges will enable the development of highly efficient, reliable, and intelligent transformerless photovoltaic inverters capable of supporting future renewable-energy infrastructures.

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