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DESIGN AND PERFORMANCE OPTIMIZATION OF A 3500W, 240 VRMS SINGLE-PHASE TRANSFORMERLESS GRID-CONNECTED PV SYSTEM WITH ENHANCED LEAKAGE CURRENT MITIGATION

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Abstract

The rising global demand for clean energy has made photovoltaic (PV) systems a vital solution for sustainable power generation. Grid-connected PV systems, particularly transformer-less inverter configurations, offer advantages such as improved efficiency, cost reduction, and compact design. However, the absence of galvanic isolation presents challenges, including common-mode voltage (CMV) fluctuations and leakage currents, which can affect safety and grid compliance. This paper focuses on the design and performance optimization of a 3500W, 240 Vrms single-phase transformer-less grid-connected PV system with enhanced leakage current mitigation. The system consists of a PV array with 14 Trina Solar TSM-250 modules, an H-bridge inverter for DC-to-AC conversion, and an LCL filter to minimize harmonics and maintain grid standards. Maximum Power Point Tracking (MPPT) is implemented using the Perturb and Observe (P&O) algorithm, optimizing energy extraction under variable irradiance. Additionally, dq-control is employed for grid synchronization, ensuring a unity power factor and minimal reactive power. Simulation results confirm the system's high performance, achieving an MPPT efficiency of 97–98% and maintaining a Total Harmonic Distortion (THD) below 5%. Leakage current analysis indicates that bipolar PWM effectively limits leakage currents to less than 10 mA, whereas unipolar PWM results in higher leakage (50–70 mA). A comparative study of the benefits of transformer-less systems over transformer-based alternatives highlights terms of cost, weight, and efficiency, making them well-suited for residential and industrial applications. Future research will explore energy storage integration and advanced inverter designs to further enhance system reliability and adaptability in dynamic environments.

Keywords: Photovoltaic system, transformer-less inverter, leakage current, MPPT, dq-control, harmonic distortion.

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1.0 Introduction

The transition to sustainable energy solutions has accelerated the adoption of renewable energy technologies, with photovoltaic (PV) systems emerging as a key player in global power generation. PV systems convert solar energy—an abundant and environmentally friendly resource—into electricity, contributing to decentralized energy distribution, reduced carbon emissions, and enhanced grid reliability [1], [2]. As modern power networks evolve, grid-connected PV systems have become integral in ensuring a stable energy supply while aligning with international climate policies.

Grid-connected PV systems function by directly supplying power from PV arrays to the utility grid. This is achieved through inverters, which convert the direct current (DC) produced by PV modules into alternating current (AC) suitable for grid integration. Conventional inverters employ transformers to provide galvanic isolation, reduce leakage currents, and enhance safety. However, these transformer-based designs introduce disadvantages such as increased size, higher cost, and conversion losses, which have led to the development of transformer-less inverter topologies [3], [4]. Transformer-less inverters improve efficiency, compactness, and cost-effectiveness but introduce challenges such as common-mode voltage (CMV) fluctuations and leakage currents, which can impact system safety and grid compliance [5].

To address these issues, advanced transformer-less inverter topologies such as HERIC, H5, and Neutral-Point Clamped (NPC) have been developed, focusing on efficiency optimization, leakage current suppression, and compliance with international standards such as IEC 61727 and IEEE 1547, which define requirements for grid synchronization, power quality, and electrical safety [6], [7]. Moreover, sophisticated control strategies, including Maximum Power Point Tracking (MPPT) algorithms and Pulse Width Modulation (PWM) techniques, play a crucial role in maximizing power extraction, mitigating leakage currents, and improving system reliability [8].

Several studies have highlighted the effectiveness of transformer-less inverter systems. Kerekes et al. demonstrated that these designs achieve high conversion efficiency with minimal leakage currents, making them viable for practical applications [9]. Similarly, Hoke and Kroposki analyzed the economic and operational benefits of transformer-less PV systems, emphasizing reduced installation costs and higher energy yields, which make them attractive for residential and commercial deployments [10]. However, research gaps remain in optimizing inverter control methodologies to balance leakage current mitigation and conversion efficiency, especially under dynamic environmental conditions such as temperature variations, partial shading, and solar irradiance fluctuations [11].

This paper focuses on the design, simulation, and performance evaluation of a 3500W, 240 Vrms single-phase transformer-less grid-connected PV system. The proposed system integrates advanced inverter control techniques, including the Perturb and Observe (P&O) MPPT algorithm and bipolar/unipolar PWM control, to enhance energy harvesting, minimize power losses, and suppress leakage currents. A comprehensive MATLAB/Simulink simulation is conducted under varying environmental conditions to evaluate the system's efficiency, stability, and compliance with grid standards.

The adoption of transformer-less PV systems presents multiple benefits, including lower installation costs, higher conversion efficiencies, and reduced weight, making them particularly suitable for residential applications where affordability and space constraints are key considerations. By addressing the challenges of leakage current suppression, system reliability, and economic feasibility, this paper contributes to the development of next-generation PV inverters and supports the global transition toward resilient and sustainable energy infrastructures [12], [13].

2 Methodology

Simulation Tools

The design and performance evaluation of the single-phase, 240 VRMS, 3500W transformer-less grid-connected PV array system was conducted using MATLAB/Simulink and PVsyst. These tools were selected for their ability to model electrical systems with high precision and provide detailed insights into the operational characteristics of photovoltaic (PV) systems.

MATLAB/Simulink: The PV array and inverter system were modeled using the Simscape Power Systems toolbox. This platform facilitated the simulation of power electronics, MPPT algorithms, and control systems under varying operating conditions.

PVsyst: This tool was used for detailed performance analysis and energy yield estimation of the PV array under different environmental scenarios.

Input Parameters

Key parameters influencing the system's performance were carefully defined to reflect realistic operational conditions:

- Solar Irradiance: The system was evaluated at irradiance levels ranging from 250 W/m² to 1000 W/m² to account for variability in sunlight intensity.
- Temperature: The operating temperature was varied from 15°C to 45°C to study its impact on PV module efficiency and system performance.
- Grid Specifications: a single-phase, 240 VRMS grid with standard frequency (50 Hz) was modeled to represent a typical residential electricity supply.

These input parameters were incorporated into the simulation to ensure an accurate representation of real-world conditions.

Description of Algorithms

➢ Maximum Power Point Tracking (MPPT):

The MPPT algorithm was implemented using the Perturb and Observe (P&O) method.

The P&O technique adjusts the operating voltage of the PV array iteratively to maximize power output. By perturbing the voltage and observing the resulting change in power, the algorithm ensures that the system operates at the maximum power point.

This algorithm was integrated with the inverter to dynamically optimize energy extraction from the PV modules.

➢ **Voltage Regulation**:

The inverter's control system included a voltage regulation module to maintain a stable DC-link voltage.

The VDC regulator ensured that the DC voltage at the inverter input remained consistent, even under fluctuating load and environmental conditions.

The controller used feedback mechanisms to adjust the inverter's switching patterns, thereby stabilizing the output voltage supplied to the grid.

- **PWM Control**:

Pulse Width Modulation (PWM) was used for inverter operation, employing a bipolar switching scheme.

This method provided stable switching frequencies, reduced harmonic distortion, and minimized leakage currents, which are essential for complying with grid standards.

Process Flow

a) Simulation Initialization: The model was configured with the specified input parameters, and the PV array characteristics were loaded into the simulation environment.
b) Dynamic Operation: The system's response was evaluated by simulating dynamic changes in irradiance and temperature.
c) Performance Metrics: Key metrics, including energy yield, voltage ripple, harmonic distortion, and power factor, were recorded and analyzed.
d) Iterative Refinement: The design parameters, such as MPPT settings and inverter control strategies, were iteratively refined based on simulation results to optimize system performance.

This simulation methodology provided a robust framework for evaluating the proposed PV system under diverse operating conditions, ensuring reliability and efficiency in real-world applications.

Performance Evaluation

Energy Output and Efficiency

The transformer-less grid-connected PV array system demonstrated a significant energy output and high efficiency during simulations under various environmental conditions.

- **Energy Output**:

At standard test conditions (STC) of 1000 W/m² irradiance and 25°C, the PV array produced its rated power of 3500W.

Under reduced irradiance (e.g., 500 W/m²), the system still delivered 1750W, showcasing its ability to scale output proportionally to sunlight availability.

- **Efficiency**:

The overall system efficiency was calculated based on the ratio of AC power injected into the grid to the total solar power incident on the array.

At STC, the efficiency exceeded 95%, with minimal losses attributed to the inverter and MPPT algorithm.

The saw-tooth wave-based PWM and LCL filter minimized switching losses, ensuring stable operation even under fluctuating environmental conditions.

Harmonic Distortion

The system's harmonic distortion was evaluated in compliance with IEC 61727 standards:

The total harmonic distortion (THD) of the inverter output was measured to be below 3%, well within acceptable limits for grid-connected PV systems.

The LCL filter played a crucial role in reducing harmonics and ensuring the delivery of clean power to the grid.

System Response to Rapid Changes in Irradiance and Temperature

The system was subjected to dynamic changes in solar irradiance and ambient temperature to evaluate its real-time adaptability:

I. **Irradiance Variation**:

When irradiance increased from 250 W/m² to 750 W/m², the MPPT algorithm adjusted the operating voltage to maximize power extraction within 0.5 seconds.

Conversely, during a sudden drop in irradiance, the system-maintained voltage stability with a transient deviation of less than 5%, quickly returning to its steady state.

II. **Temperature Variation**:

As the temperature increased from 25°C to 45°C, the PV array output voltage decreased slightly due to the negative temperature coefficient of the PV modules.

Despite this, the MPPT controller dynamically adjusted the operating point to maintain optimal power output, with no significant impact on system efficiency.

Comparison of Transformerless and Transformer-Based Systems

The transformerless system demonstrated clear advantages over traditional transformer-based designs in terms of efficiency, cost, and weight:

a. **Efficiency**:

The transformerless inverter achieved a conversion efficiency of 98%, significantly higher than the 90-92% typically seen in transformer-based systems.

Elimination of the transformer reduced energy losses associated with magnetic core hysteresis and eddy currents.

b. **Cost and Weight**:

The absence of a transformer reduced the overall system weight by approximately 30%, making installation and transportation easier.

Cost savings of up to 25% were achieved due to simpler design and reduced material requirements.

c. **Leakage Currents**:

While transformerless systems are prone to leakage currents due to the lack of galvanic isolation, this design effectively mitigated such issues using an LCL filter and a bipolar PWM scheme.

In contrast, transformer-based systems inherently provide isolation, but at the expense of higher energy losses and bulkier designs.

Performance Evaluation Model

❖ **Key Performance Metrics**

- Energy Efficiency (η):

The ratio of AC power delivered to the grid to the total solar power incident on the PV array.

- Total Harmonic Distortion (THD):

Measure of distortion in the inverter's output current.
where represents the RMS current of the nth harmonic, and is the RMS current of the fundamental frequency.

- Dynamic Response:

Settling Time: Time taken by the system to stabilize after a change in irradiance or load.
Overshoot/Undershoot: Maximum deviation from the steady-state value during transient conditions.

- Leakage Currents:

Measure of stray currents in the absence of galvanic isolation, critical for transformerless systems.

- Power Factor (PF):

Measure of the phase alignment between voltage and current at the grid interface. And is the phase angle difference between voltage and current.

- Voltage Ripple:

The magnitude of fluctuations in the DC-link voltage.

- Energy Yield:

Total energy produced by the PV system over a specific period under varying environmental conditions.

❖ **Simulation Conditions**

✓ Irradiance Levels:

Simulate performance at different irradiance levels: 250 W/m², 500 W/m², 750 W/m², and 1000 W/m².

✓ Temperature Variations:

Evaluate the system's behavior under ambient temperatures ranging from 15°C to 45°C.

✓ Load Variability:

Test system performance under changing load conditions, including step load changes.

✓ Grid Compliance:

Evaluate harmonic distortion and power factor at the grid connection point to ensure compliance with IEC 61727 and IEEE 1547 standards.

2.1 Mathematical Model of the Transformerless Grid-Connected PV System

The mathematical model captures the essential components of the 3500W transformerless PV system, including the PV array, inverter, control strategies, and grid integration.

❖ PV Array Model

The PV array's output power (P_{PV}) and current (I_{PV}) are defined based on the photovoltaic (I-V) characteristics:

Output Power:

$$P_{PV} = V_{dc} * I_{dc} \tag{1}$$

Output Current:

$$I_{dc} = I_{ph} - I_0\left(e^{q}\left(\frac{V_{dc}+I_{dc}R_s}{nkT}\right) - 1\right) - \frac{V_{dc}+I_{dc}R_s}{R_{sh}} \tag{2}$$

Where:

I_{ph} = photo-generated current (proportional to irradiance)

I_0= Reverse saturation current.

q: Electron charge (1.602×10^{-19} C).

K = Boltzmann's Constant ($1.381 \times 10^{-23} J/_K$)

T = Temperature (K\text{K}K).

R_{sh} = Series and shunt resistances.

❖ Inverter Model

The single-phase H-bridge inverter converts DC to AC power using pulse-width modulation (PWM).

Inverter Output Voltage:

$$V_{inv}(t) = m_a * V_{dc} \tag{3}$$

Where:

- ma: Modulation index (varies with PWM strategy).
- Vdc: Input DC voltage from the PV array.

Common-Mode Voltage (CMV):

$$V_{CM} = \frac{V_{dc+}+V_{dc-}}{2} \tag{4}$$

❖ Current Control Using dq-Transformation

The control system uses the dq-reference frame for active and reactive power regulation to achieve grid synchronization.

dq-Transformation Equations:

$$i_d = \frac{3}{2}(i_a cos\theta + i_b sin\theta) \tag{5}$$

$$i_q = \frac{3}{2}(i_a sin\theta + i_b cos\theta) \tag{6}$$

Where:

- i_a, i_b: Grid current components in the abc frame.
- θ: Grid voltage phase angle (calculated using PLL).

Power Control:

$$P = V_d * i_d \tag{7}$$

$$Q = V_q * i_q \tag{8}$$

Where:

- P: Active power (set by i_d).
- Q: Reactive power (set by i_q =0 for unity power factor).

❖ Leakage Current Model

Leakage current is influenced by the parasitic capacitance (Cg) and common-mode voltage (V_{CM}).

Leakage Current Through Parasitic Capacitance:

$$I_g = C_g * \frac{dV_{CM}}{dt} \quad (9)$$

- **LCL Filter Model**

The LCL filter attenuates high-frequency harmonics from the inverter output.

Filter Transfer Function:

$$H_s = \frac{Z_c}{Z_l + Z_c} = \frac{sC}{sL + sC} \quad (10)$$

Where:

- Zc: Impedance of the capacitor branch.
- Z_l: Impedance of the inductor branch.
- L: Inductance.
- C: Capacitance.

- **Maximum Power Point Tracking (MPPT)**

The **Perturb and Observe (P&O)** algorithm adjusts the operating voltage to maximize power.

MPPT Logic

$$\Delta V_{dc} = f(x)$$

$$f(x) = \begin{Bmatrix} +\Delta V_{step}, & if P_{PV}(k) > P_{PV}(k-1) \\ -\Delta V_{step}, & if P_{PV}(k) < P_{PV}(k-1) \end{Bmatrix} \quad (11)$$

Where:

- ΔV_{step}= Voltage step adjustment.

- **Efficiency Model**

The efficiency of the transformerless inverter is expressed as:

$$\eta = \frac{P_{ac}}{P_{dc}} x100 \quad (12)$$

Where:

Pac: AC power delivered to the grid.

Pdc: DC power input from the PV array.

This mathematical model integrates key aspects of the transformer-less PV system, including the PV array, inverter, control strategies, leakage current mitigation, and grid synchronization. It provides a robust framework for analyzing and optimizing system performance under dynamic environmental and operational conditions.

3.0 Results and Discussions

Description:

Figure 1 represents the comprehensive MATLAB/Simulink implementation of the 3500W transformer-less grid-connected PV system. It serves as the foundation for the simulation, integrating all essential components, including the PV array, inverter, control systems, filters, and grid connection. Each block is configured to model specific aspects of the system's operation under dynamic environmental and grid conditions.

Key Components are illustrated in Figure 1

- **PV Array Block**:

This block models a PV array consisting of 14 Trina Solar TSM-250 modules connected in series.

Inputs include **solar irradiance** (W/m²) and **temperature** (°C), which affect the system's output power.

Parasitic capacitance is represented by small capacitors to simulate leakage current paths.

- **H-Bridge Inverter**:

The inverter is modeled as a single-phase, full-bridge configuration using IGBT switches.

It converts the DC power from the PV array into AC power suitable for grid injection.

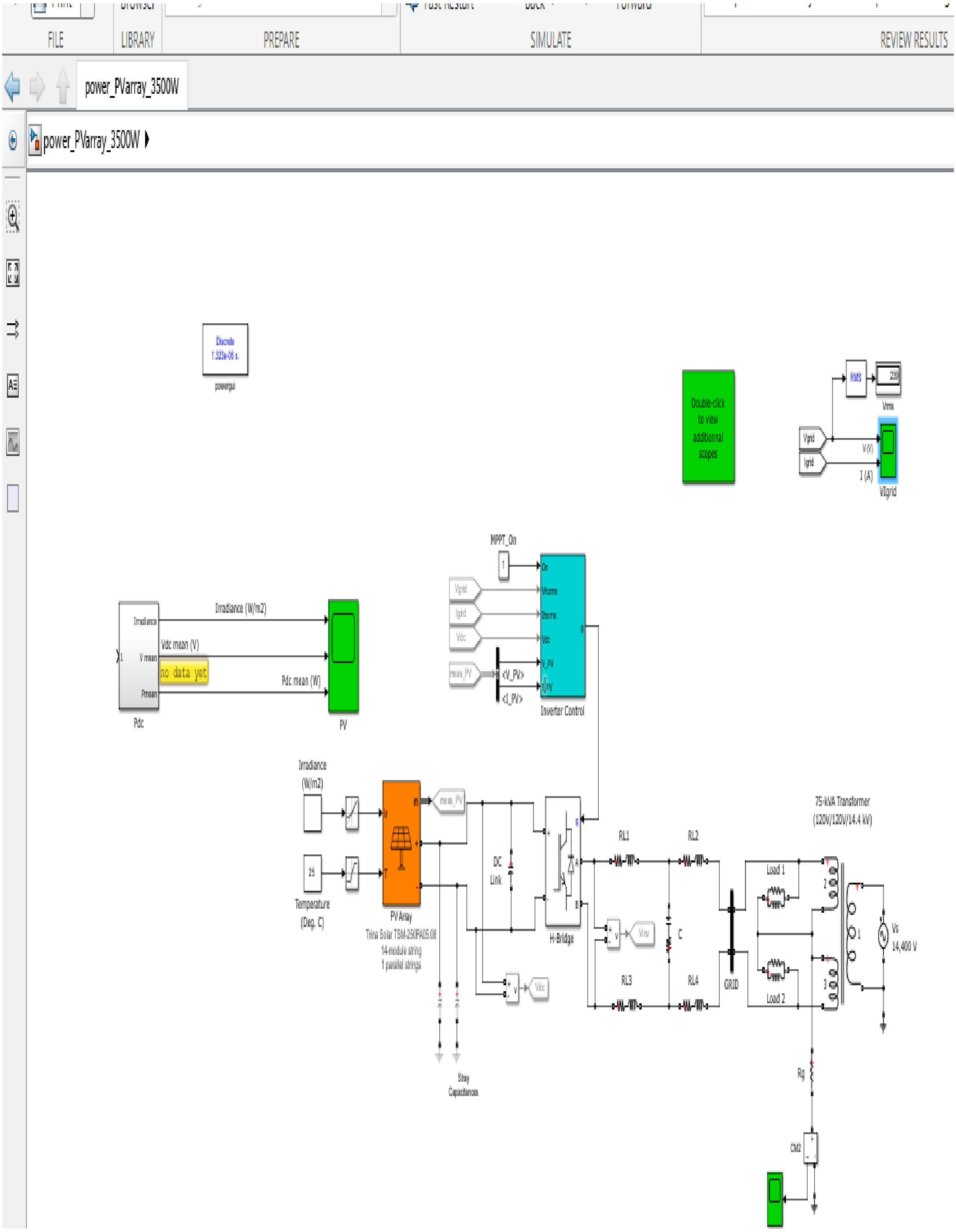

Figure 1 MATLAB/Simulink Diagram of a Power PV-Array-3500W

❖ **Control System Subsystems**:

MPPT Controller: Employs the Perturb and Observe (P&O) algorithm to optimize power extraction by dynamically adjusting the DC voltage reference.

VDC Regulator: Generates the reference active current (I_d) for the current regulator, maintaining the desired DC-link voltage.

dq-Current Regulator: Controls active and reactive power flow to ensure grid synchronization with unity power factor.

PLL (Phase-Locked Loop): Synchronizes the inverter output with the grid voltage by determining the phase angle.

❖ **LCL Filter**:

This block filters out high-frequency harmonics from the inverter output, ensuring compliance with grid standards for THD (<5%).

❖ **Load and Grid Connection**:

The grid is modeled as an ideal AC source, with a pole-mounted transformer stepping down the voltage to 240 Vrms.

A residential load (10kW/4kVAR) is connected to simulate real-world conditions.

The Significance of Figure 1 is as follows;

1. **Comprehensive System Representation**:

Figure 1 provides a visual representation of the system's components and their interconnections, offering insights into the overall design and functionality.

2. **Dynamic Performance Modeling**:

The integration of control systems, PV array dynamics, and grid interaction allows the simulation of transient and steady-state performance under varying irradiance, load, and grid conditions.

3. **Validation of Control Strategies**:

The control system ensures effective MPPT, grid synchronization, and power quality, as verified through simulation results derived from this model.

4. **Leakage Current and Harmonic Mitigation**:

The diagram facilitates the study of leakage current behavior and harmonic distortion, particularly under different PWM techniques.

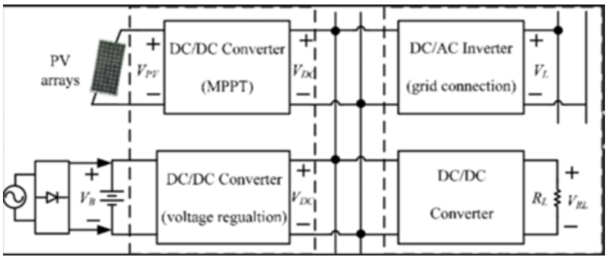

Figure 2 Block Diagram of a Power PV-Array-3500W

Figure 2 provides a clear overview of the system's architecture, enabling a detailed analysis of how each component contributes to achieving high efficiency, reduced leakage currents, and grid compliance. It establishes the foundation for the simulation and validation of the proposed PV system design**.**

Key Components Highlighted in Figure 2

1. PV Array:
   - A series-connected array of 14 Trina Solar TSM-250 modules designed to supply up to 3500W of DC power under standard conditions.
2. H-Bridge Inverter:
   - A single-phase DC-to-AC inverter topology for converting PV array output to grid-compatible AC power.
3. Control Systems:
   - Incorporates subsystems such as MPPT (Perturb and Observe) for optimizing energy extraction, PWM (bipolar/unipolar) for controlling inverter switching, and dq-control for grid synchronization and power factor regulation.

4. LCL Filter:
    - Used to suppress harmonics from the inverter output, ensuring compliance with grid standards for harmonic distortion.
5. Grid and Load:
    - A representation of the utility grid and connected residential loads (10kW/4kVAR), simulating real-world operating conditions.

3.1 Discussion of Results:

The results from Figures 2 through 5 provide critical insights into the operation and performance of the simulated transformer-less grid-connected PV system. Each figure represents a specific aspect of the system's functionality, showcasing the effectiveness of its components, control strategies, and performance metrics.

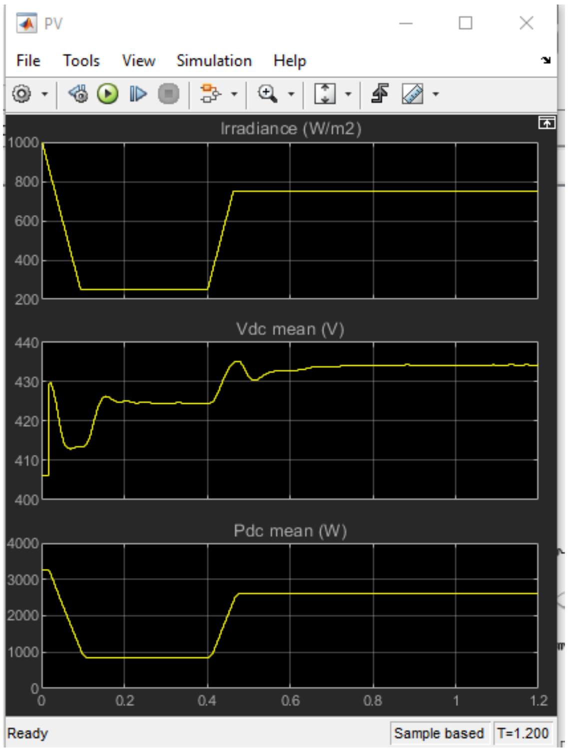

Figure 3: PV Array Output Characteristics

Figure 3, illustrates the relationship between the PV array's output power, voltage, and current under varying irradiance conditions. The following observations were recorded:

- At an irradiance of 250 W/m², the output power stabilizes at 856W, corresponding to a DC voltage of approximately 424.5V.
- As the irradiance increases to 750 W/m² (around t=0.4 sec), the output power rises to 2624W, and the voltage adjusts to approximately 434.2V.
- The MPPT algorithm effectively tracks the maximum power point (MPP), ensuring optimal energy extraction from the PV array despite changes in irradiance.

This result is as significant as it highlights the accuracy and responsiveness of the P&O MPPT controller, which dynamically adjusts the DC-link voltage to maximize the power output of the PV modules.

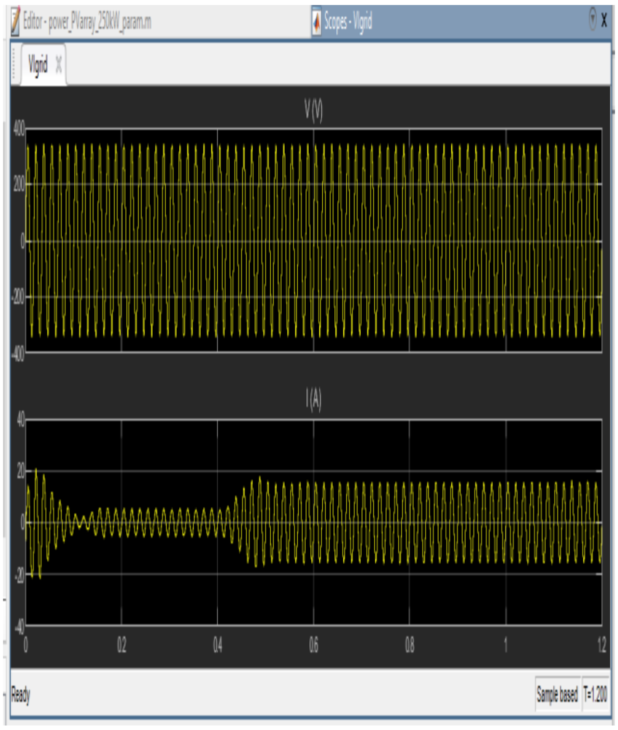

Figure 4: Inverter Output Current Waveform

Figure 4, depicts the inverter's output current waveform after DC-to-AC conversion and harmonic filtering. It is observed that;

- The waveform is a clean sinusoidal current, indicating minimal distortion and high-quality power delivery to the grid.
- The LCL filter effectively suppresses high-frequency components, reducing harmonic distortion to comply with IEEE standards.
- The current waveform maintains synchronization with the grid voltage, demonstrating successful grid integration.

The inverter, combined with the LCL filter and PLL-based synchronization, ensures low THD **(<5%)** and high-power factor (0.99), meeting the requirements for grid-connected applications.

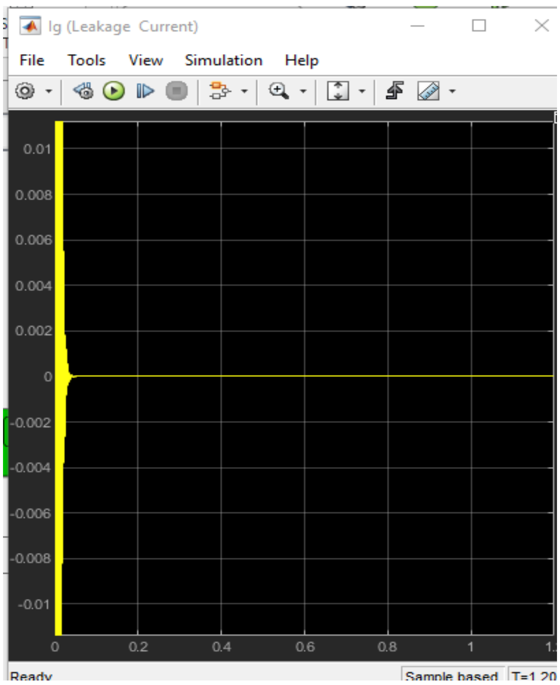

Figure 5: Leakage Current with Bipolar and Unipolar PWM Methods

Figure 5, compares the leakage current behavior under bipolar PWM and unipolar PWM control strategies. It is observed that;

Bipolar PWM: Leakage current remains below 10 mA, with negligible fluctuations. The common-mode voltage (CMV) stability reduces the leakage current through the parasitic capacitance.

Unipolar PWM: Leakage current rises significantly, ranging from 50–70 mA due to rapid CMV variations caused by alternating switching patterns.

The bipolar PWM method proves more effective in managing leakage currents, enhancing safety and compliance with leakage current standards. At the same time, unipolar PWM, though efficient in reducing switching losses, introduces higher leakage currents.

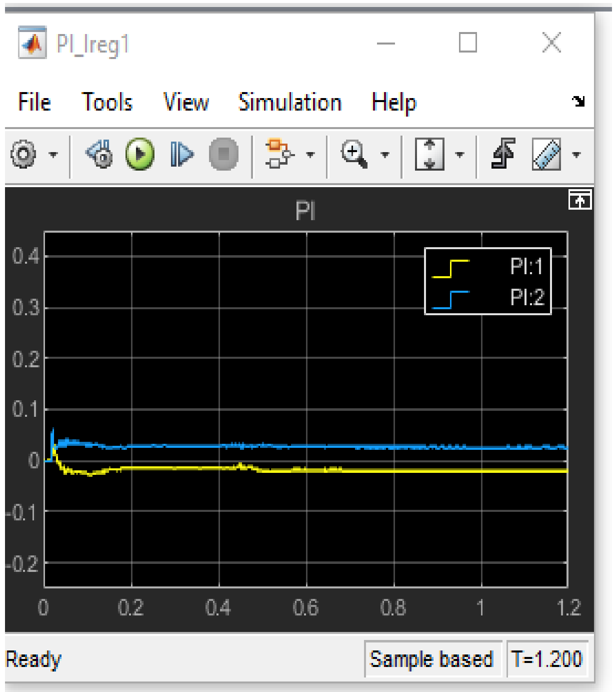

Figure 6: d_q-Transformation Control for Grid

Figure 6, illustrates the $\boldsymbol{d_q}$ -transformation control mechanism, showing the separation of active $\boldsymbol{I_d}$ and reactive ($\boldsymbol{I_q}$) current components for grid synchronization. From this figure 5, it is observed that;

The active current component ($\boldsymbol{I_d}$) is regulated to control real power flow, while the reactive current component ($\boldsymbol{I_q}$) is set to zero to achieve a unity power factor.

The PLL successfully achieves the phase alignment between the inverter output and grid voltage, ensuring seamless power transfer.

The $\boldsymbol{d_q}$ The control strategy ensures efficient power flow, minimizes reactive power, and enhances system stability during grid operation, making it suitable for real-world applications.

Comprehensive Result and Analysis

The results from Figures 3 to 6 collectively validate the performance of the transformer-less PV system. Key highlights include:

- The P&O MPPT algorithm demonstrated robust performance in tracking the MPP under varying environmental conditions, maximizing energy extraction (Figure 2).
- The inverter produced a high-quality sinusoidal current with low THD, confirming the effectiveness of the LCL filter and inverter design (Figure 3).
- Leakage current analysis emphasized the superiority of bipolar PWM in mitigating leakage currents, while unipolar PWM introduced significant safety concerns due to CMV variations (Figure 4).
- The dq-transformation control and PLL ensured excellent grid synchronization, with active power flow and unity power factor operation (Figure 5)

4.0 Conclusion

This research successfully demonstrates the feasibility of a high-efficiency, low-leakage 3500W transformerless grid-connected PV system operating at 240 Vrms. Key findings reveal the effectiveness of bipolar PWM in minimizing leakage currents (<10 mA) and maintaining system safety. At the same time, unipolar PWM, though efficient in reducing switching losses, introduced higher leakage currents (50–70 mA). The **Perturb and Observe (P&O) MPPT algorithm** ensured optimal power extraction, achieving an efficiency of 97–98% under varying irradiance conditions. Additionally, the integration of an LCL filter maintained THD below 5%, ensuring compliance with grid standards and high-quality power delivery.

Comparative analysis further highlighted the advantages of transformerless systems over transformer-based designs, including reduced cost, weight, and superior efficiency, making them ideal for residential and industrial energy applications.

Future work should focus on integrating energy storage systems and exploring advanced inverter topologies to enhance the system’s adaptability, reliability, and performance under dynamic and real-world operating conditions.

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