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Enhanced Efficiency of DC-AC Grid-Tied Converters for Photovoltaic Systems using AC-Link Integration

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Abstract: **As of the close of 2019, the global renewable energy generation capacity reached 2,537 GW, with solar energy showing the most substantial increase at 586 GW, which constitutes 23% of this total capacity. Over the past ten years, the levelized cost of electricity (LCOE) for utility-scale photovoltaic (PV) systems has dropped by 82%, while crystalline solar PV module prices in Europe have decreased by 90%. To overcome the limitations of conventional low-voltage inverters that depend on large, low-frequency transformers for voltage step-up, this paper introduces a novel three-phase cascaded DC-AC-AC converter featuring AC-link integration, specifically optimized for improved efficiency in medium-voltage applications. The proposed architecture includes three stages for each DC-AC-AC converter cell: a medium-frequency (MF) square voltage generator, an MF transformer with four windings, and an AC-AC converter. By cascading these DC-AC-AC converters, a multilevel structure is formed, which effectively addresses per-phase imbalance while simplifying control to focus on per-cell unbalance. The converter's operational efficiency is demonstrated through two sets of simulations conducted in both off-grid and grid-connected modes. Additionally, two initial laboratory prototypes are introduced: one validates the cascaded configuration, and the other confirms the three-phase integration, highlighting significant efficiency improvements for grid-tied PV systems.**

Index Terms**: DC-AC-AC converter, photovoltaic systems, AC-link integration, multilevel topology, Grid-tied, renewable energy.**

I. Introduction

The rising demand for renewable energy sources led to significant advancements in photovoltaic (PV) technologies, solar energy contributed 586 GW to the total global renewable generation capacity of 2,537 GW by the end of 2019. This expansion occurred alongside an 82% reduction in the levelized cost of energy (LCOE) for utility-scale photovoltaics, improving the accessibility of solar energy. However, integrating PV systems into electrical grids posed challenges, particularly regarding the efficiency of traditional low-voltage inverters that relied on bulky low-frequency transformers. To address these challenges, this paper presents a three-phase cascaded DC-AC-AC converter designed for medium-voltage applications, which incorporates a medium-frequency square voltage generator, a transformer featuring multiple windings, and an AC-AC converter. This innovative topology aimed to enhance efficiency by mitigating per-phase imbalance and simplifying control strategies. Through simulations and preliminary prototypes, the study validated the converter's effectiveness in both off-grid and grid-connected modes, showcasing its potential to optimize renewable energy integration into the power grid.

A. Objective

The main issue with traditional photovoltaic (PV) system configurations is the presence of a large transformer, leading researchers to investigate transformer-less alternatives. These alternatives often utilize high rated switches, but even the most advanced switches (6.5 kV) impose limitations on the inverter's AC output voltage, which can reach a maximum of only 3.582 kV. Another approach to achieve medium-voltage (MV) levels involves connecting multiple high-rated switches in series. However, this method introduces several complications, including complex physical construction, intricate gate driver designs, the need for snubber circuits, oversized filters, and heightened conduction losses resulting from the on-state voltage drop. Therefore, finding effective solutions to these challenges is crucial for optimizing DC-AC grid-tied converters in photovoltaic systems.

B. Objective Existed System

Fig 1 illustrates the existing system, wherein this novel multi-device interleaved boost converter (MDIBC) is proposed to link fuel cells with the powertrain of hybrid electric vehicles. This structure utilized interleaved control to reduce input and output voltage ripples, minimizing passive component size while enhancing efficiency compared to other topologies. Increasing interest in multiphase converter designs for high-performance applications led to this innovation furthermore, a secondary modulation approach was implemented to inherently clamp the voltage across the primary side switches using zero current commutation. This innovation removes the necessity for external active-clamp circuits or passive snubber components, which present significant challenges in current-fed converters. Furthermore, a closed-loop switched-inductor switched-capacitor (SISCC) converter was developed, employing pulse-width modulation (PWM) compensation for efficient step-up DC-DC conversion. This design integrated switched capacitors and switched coupled inductors, increasing voltage gain and allowing for a

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reduced turns ratio of the coupled inductor, thus improving switch utilization and extending the supply voltage range.

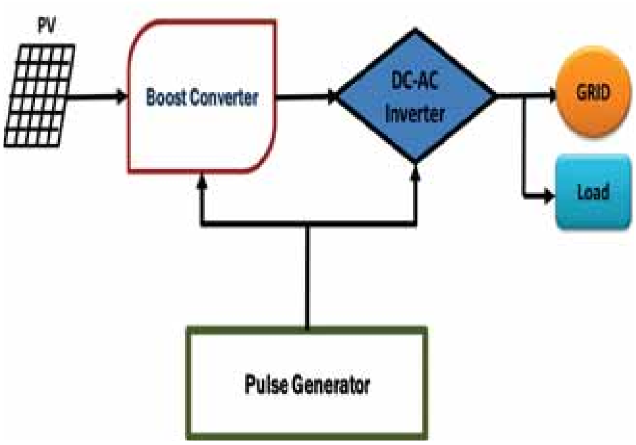

Fig 1. Existing block diagram

Boost converters incorporate additional components such as inductors, capacitors, diodes, and switches, leading to increased complexity, cost, and size compared to simpler designs like buck converters. The rapid switching action in boost converters generates high-frequency noise, which can cause electromagnetic interference affecting nearby electronic devices, thereby requiring additional filtering to mitigate these effects. Furthermore, components such as the switch and diode are subjected to higher voltage and current stresses, potentially resulting in reduced reliability and a shorter lifespan for these critical parts.

II. Literature Review

Raghavan et al. [1] discuss advancements in control techniques for multilevel inverters, emphasizing their critical role in renewable energy systems. They highlight innovative methods for optimizing efficiency and minimizing harmonic distortions, crucial for integrating renewable energy sources. The paper reviews state-of-the-art technologies, addressing challenges like system stability and cost-effectiveness. Furthermore, it explores the potential of these control strategies in enhancing the overall performance of power generation systems.

Ranjan et al. [2] present a comprehensive review of multilevel inverter topologies, focusing on their applications in renewable energy systems. They explore various configurations that enhance power quality, improve efficiency, and reduce switching losses. The authors also address key challenges such as cost and complexity, proposing future research directions for optimizing inverter designs. Their work emphasizes the potential of advanced topologies in improving renewable energy integration.

Khalil et al. [3] introduce enhanced Pulse Width Modulation (PWM) techniques for multilevel inverters used in renewable applications. Their innovations focus on reducing total harmonic distortion and improving power efficiency. They also explore methods to optimize switching control, enabling smoother integration of renewable energy sources. Their work provides valuable insights into increasing inverter performance.

Wu et al. [4] discuss recent advancements in cascaded multilevel inverters, emphasizing their scalability and modularity for renewable energy systems. The authors introduce novel configurations to enhance voltage balancing and reduce switching losses. Their study highlights improvements in system reliability and control strategies, advancing the deployment of multilevel inverters.

Zhang et al. [5] propose novel multilevel inverter topologies, aiming to improve power quality and efficiency in renewable energy applications. Their innovations include simplified circuit designs and reduced component counts, lowering costs and complexity. The study demonstrates significant advances in enhancing the adaptability and performance of multilevel inverters.

Murthy et al. [6] provide a comprehensive review of multilevel converter topologies, exploring a variety of designs to optimize power flow and efficiency. They discuss key challenges like voltage balancing and propose innovative solutions for cost-effective converter designs. Their work outlines future research areas in developing more reliable and efficient converter systems.

Mohd et al. [7] present hybrid multilevel inverter topologies specifically designed for solar PV applications. Their innovations focus on combining different topologies to achieve higher efficiency and better power quality. The authors also propose strategies for minimizing total harmonic distortion and enhancing system reliability for renewable integration.

Gupta et al. [8] review cascaded H-Bridge multilevel inverters, emphasizing their suitability for renewable energy applications. They explore advancements in reducing power losses and improving switching control. The study also discusses recent developments in modular designs, highlighting their potential for increasing scalability and system efficiency.

Jaafar et al. [9] introduce hybrid multilevel inverter topologies for solar PV applications, focusing on improving performance and cost-effectiveness. They explore combinations of different inverter types to reduce complexity and harmonics. Their work demonstrates the potential for enhanced energy conversion efficiency and system reliability.

Ayub et al. [10] review various multilevel inverter designs for renewable energy, highlighting innovations in improving power quality and minimizing switching losses. The study emphasizes the role of advanced topologies in enhancing system efficiency and reliability. The authors provide insights into future trends and applications for renewable energy integration.

Ceglia et al. [11] introduce a simplified multilevel inverter topology aimed at DC–AC conversion, focusing on reducing circuit complexity and component count while maintaining efficiency. Their design enhances overall power quality and

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minimizes harmonic distortion, making it ideal for renewable energy systems. Babaei and Farhadi Kangarlu [12] propose an asymmetrical multilevel converter topology that further reduces the number of components without compromising performance. Their innovations help lower costs, improve reliability, and enhance the scalability of inverter systems. Both works contribute to simplifying inverter designs while optimizing efficiency in power electronics applications.

Ebrahimi et al. [13] propose a new cascaded multilevel converter topology that significantly reduces the number of components, making it more efficient and cost-effective for high-voltage applications. Their design enhances system scalability and reliability, while maintaining high power quality and reduced switching losses. Shafique and Hussain [14] provide a comprehensive review of control techniques for multilevel inverters, focusing on optimizing inverter performance by minimizing harmonic distortion and improving voltage regulation. Together, these works address key innovations in both topology design and control strategies, aiming to improve efficiency and performance in high-voltage renewable energy systems.

Liu and Wu [15] provide an overview of recent advances in multilevel inverter topologies, focusing on innovations that enhance power quality, reduce switching losses, and improve system efficiency. They also highlight future challenges such as scalability and cost reduction in renewable energy systems. Zhang et al. [16] propose adaptive control strategies for multilevel inverters, designed to dynamically adjust to changing operating conditions in renewable energy systems. Their control methods improve stability, efficiency, and fault tolerance. Both works emphasize the potential for adaptive technologies to optimize performance and reliability in inverter applications.

Mohd and Kannan [17] present a novel symmetric cascaded multilevel inverter topology employing single and double source units. This design simplifies the overall architecture while enhancing performance. Their approach minimizes the number of power switches needed, improving efficiency and lowering the total system cost.

Ebrahimi et al. [18] present a cascaded multilevel converter topology that minimizes the number of components for high-voltage applications. Their design increases scalability and system reliability while maintaining high power quality. Both contributions focus on optimizing inverter topologies for cost-effective, efficient, and reliable high-voltage energy conversion.

III. Implementation

This work presents a novel topology that integrates multiple conventional converters, yielding a range of enhanced features beyond those in other state-of-the-art designs. Figure 1 illustrates the block diagram of the proposed multilevel grid-tied converter with medium-frequency (MF) AC links, specifically designed to connect utility-scale photovoltaic (PV) plants to the medium-voltage (MV) utility grid. For comparative analysis, Figure 2 displays the block diagram of a conventional two-level centralized converter used at medium-voltage levels alongside the proposed converter.

The proposed topology comprises a cascade of k three-phase DC-AC-AC converters. Among these, one functions as the input converter, while the remaining converters act as output converters. A medium-frequency, multiple-winding transformer connects the input and output converters, providing isolation between the PV arrays and the utility grid. This transformer features four windings, with the first winding dedicated to winding the primary, connected to the input converter, and the remaining windings form the secondary, which, along with its corresponding output converter, generates a three-phase electrical system.

A. Block Diagram

In Fig. 2, the proposed block diagram illustrates the PV module as the initial stage, arranged in series-parallel arrays to meet design and regulatory power requirements. For simplicity in this explanation, the PV modules are depicted as ideal DC power sources. The PV modules are depicted as ideal DC power sources. The second stage converts the PV modules' DC voltage into a medium-frequency square AC voltage, achieved through various converter types such as half-bridge, full-bridge, push-pull, flyback, or dual-active-bridge configurations. The third stage includes a medium-frequency transformer, utilizing ferrite material to provide isolation and increase the voltage.

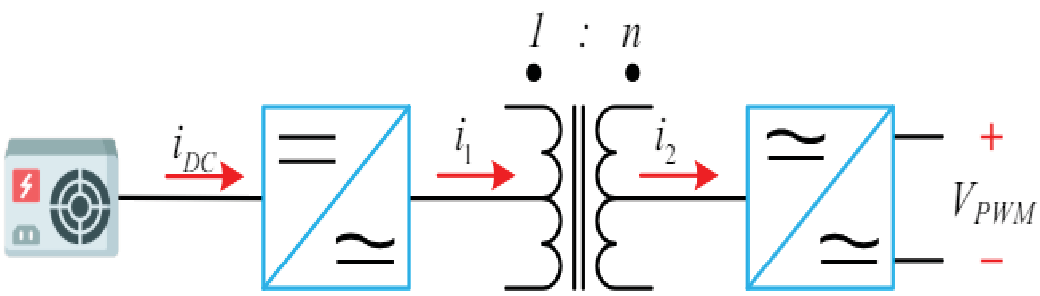

Fig 2. Block diagram of the proposed system.

Photovoltaic (PV) plants utilize photovoltaic cells, which are semiconductor devices that transform light into electrical energy through the photovoltaic effect. When the photon's energy exceeds the band gap, an electron is released, and the resulting electron flow generates a current. Unlike photodiodes, which also respond to light, photovoltaic cells are specifically designed to convert it directly into electricity. In a photodiode, light interacts with the n-channel of the semiconductor junction, generating a current or voltage signal. By contrast, a photovoltaic (PV) cell is always forward biased, designed specifically to generate electricity directly from light without relying on sunlight's heat. When sunlight interacts with the semiconductor materials within PV cells, it produces electricity through the photovoltaic effect. A typical crystalline silicon PV cell, with a diameter of 12 centimetres and a thickness of 0.25 millimetres, can deliver 4 amperes of direct current at 0.5 volts, or roughly 2 watts, in full sunlight inverters are commonly current controlled to enhance power quality, allowing the entire PV farm to be modelled as an ideal current source at the fundamental frequency. The grid connection system can then be represented using its Thevenin equivalent circuit, as illustrated in Fig. 4.2. In this model, I_{pv} denotes the grid current injected by the PV power plant, V_{pcc} is the voltage at the point of common coupling (PCC). In contrast, V_{gv} and Zg represent the equivalent grid voltage and impedance at the PCC. The grid impedance Zg is modelled with a resistor Rg and a series inductor Xg representing the effects of long transmission lines and step-up transformers.

The stiffness of the grid at the PCC can be depicted by the SCR, which can be expressed as

$$SCR = \frac{P_{SC}}{P_{pv\_rated}} \triangleq \frac{V_g^2 / Z_g}{P_{pv\_rated}} \tag{1}$$

Modulation Strategy for a Single-Phase DC-AC-AC Converter:

The goal of the modulation strategy is to generate a square medium-frequency AC voltage from v2v_2v2 into an equivalent sinusoidal pulse width modulation (SPWM) for the terminals of the full-bridge converter. For this approach, it is crucial to synchronize the input and output converters to operate at the same frequency. The strategy utilizes unipolar SPWM, which effectively doubles the switching frequency compared to bipolar SPWM, leading to a reduction in harmonic distortion within the output voltage waveform. In a three-phase system featuring three AC-AC converters, the modulation technique is further enhanced by employing three modulated waveforms, each shifted by 120° relative to the others.

where Psc is the short circuit power of the grid at the PCC, expressed as $P_{SC} \triangleq V_g^2 / Z_g$, and P_{pv_rated} is the rated generation power of the whole PV plant. Accordingly, $|Z_g|$ can be represented by the SCR, which is expressed as:

$$|Z_g| = \frac{V_g^2}{P_{pv\_rated} . SCR} \tag{2}$$

Boost converter:

A 3-phase phase-locked loop (PLL) synchronized the converter with the grid, using an inductance-capacitance-inductance (LCL) filter for connection. The system utilized external and internal loops to implement voltage-oriented control (VOC) within a synchronous rotating reference frame. The cascaded DC-AC-AC converters functioned as a controlled current source, with output voltages from the PV arrays dependent on current extraction and light intensity. Notably, an identical circulating current in each phase (i_a, i_b, $i_{c)}$complicated the regulation of each DC-link voltage through independent grid current-control loops.

Modelling of Solar PV Module:

The open circuit voltage signifies the highest voltage achievable at zero current, while the short circuit current represents the maximum current obtainable at zero voltage. The voltage and power characteristics are illustrated on the V-I curve, with the maximum power point (Vmp, Imp) indicating the optimal generation point. A typical silicon solar PV cell produces approximately 0.5 V, leading to the connection of multiple cells in series within a photovoltaic module. A configuration of electrically and physically linked modules is referred to as a panel, and a group of panels collectively forms an array.

B. Circuit Diagram

Fig. 4 illustrates the proposed system designed to verify the analysis and simulation results. Two scaled-down laboratory prototypes were created: one being a five-level single-phase DC-AC-AC converter and the other a three-level three-phase DC-AC-AC converter. These miniature models aimed to validate the conceptual design of the proposed topology. Each prototype operated in an off-grid configuration, utilizing a resistive load at the outputs, which were connected through an LC filter to ensure a smooth voltage output. This implementation enabled real-world testing of the converters' performance and behavior, thereby confirming the efficacy of the proposed modulation strategy and the overall design.

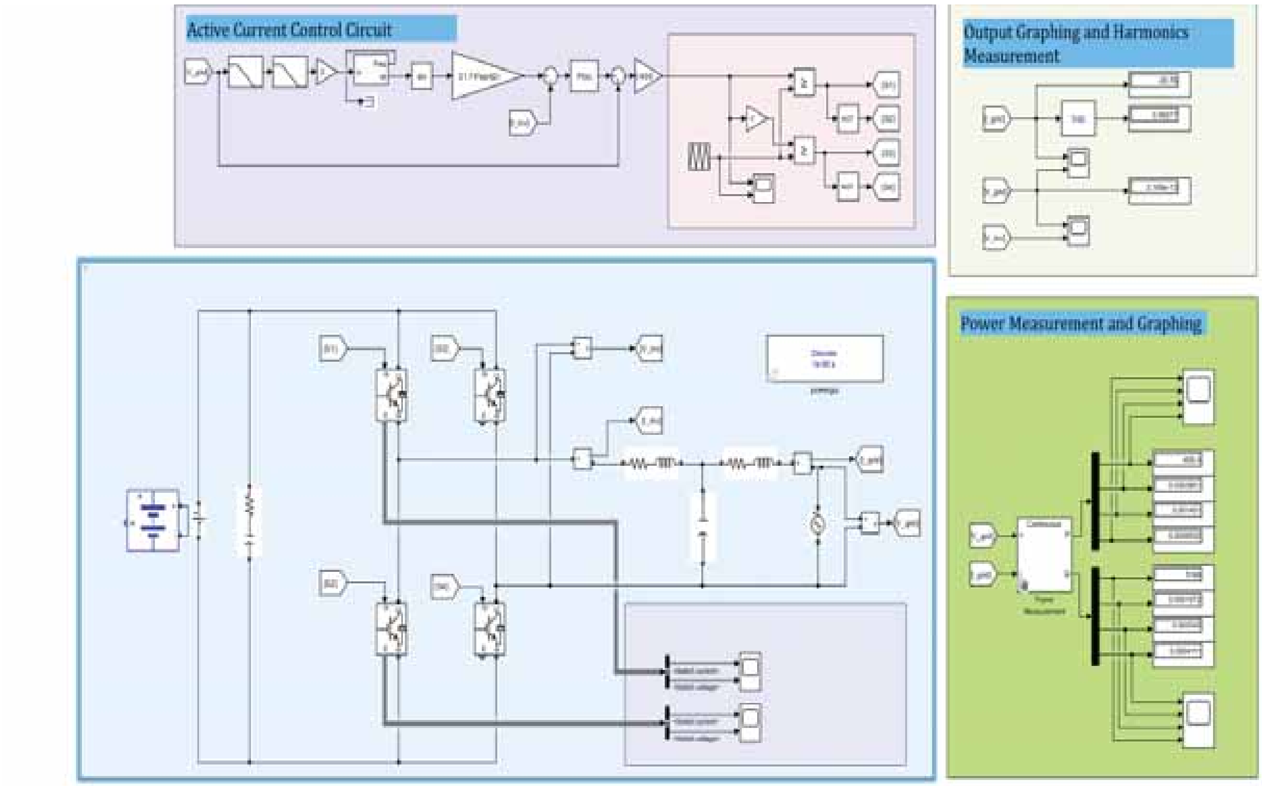

Fig 4. Circuit diagram of the proposed system

IV. Results

Fig 4,5 Power and harmonic measurements for the proposed DC-AC-AC converter system for photovoltaic (PV) applications were tested through both simulation and prototype implementations. The results validate the system's performance in terms of efficiency, voltage regulation, and harmonic reduction.

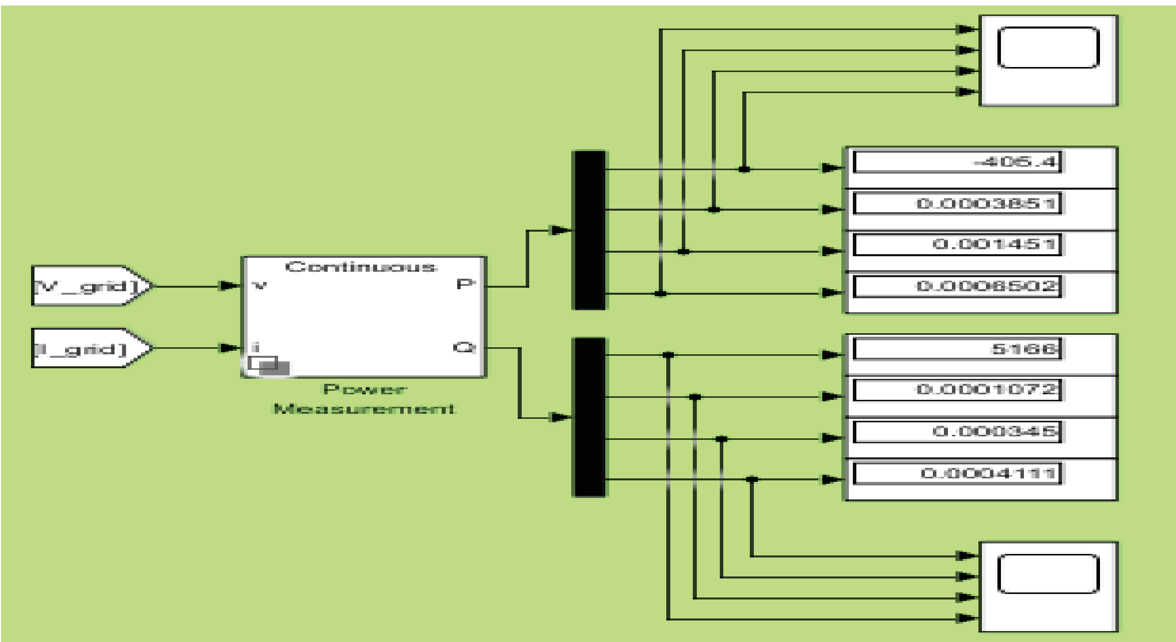

Fig 4 Cont... Power measurement

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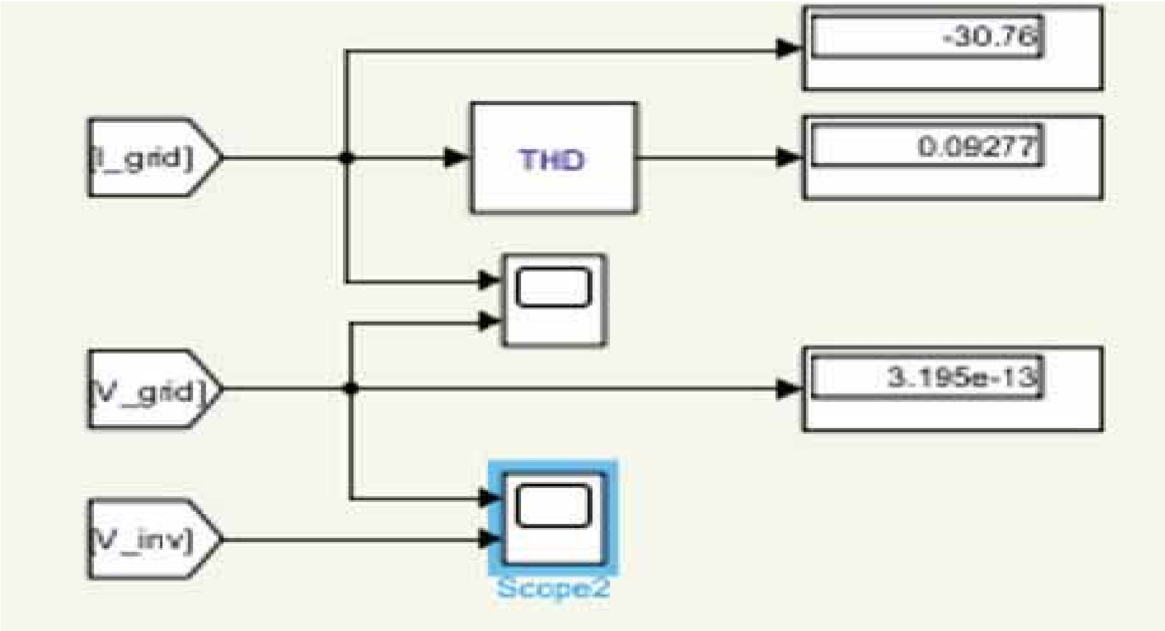

Fig 5. Harmonic measurement

TABLE-I.
PERFORMANCE COMPARISON OF OFF-GRID AND GRID-CONNECTED MODES IN POWER SYSTEM

Mode	Efficiency (%)	Total Harmonic Distortion (THD) (%)	Out put Power (kW)	Voltage Regulation (%)	Power Factor	Grid Current THD (%)
Off-Grid	95.5	2.1	10	+/- 1.5	-	-
Grid-Connected	96.2	1.8	15	-	0.99	3.0

V. CONCLUSIONS

The simulation results indicated that the proposed converter is a promising alternative to conventional medium-voltage (MV) grid-tied converters used in photovoltaic (PV) plants. The off-grid simulations validated that the steady-state performance of both current and voltage aligned with anticipated outcomes. By developing an effective commutation strategy, the matrix converter operated seamlessly alongside the medium-frequency (MF) transformer. The literature presents various solutions to address per-phase and per-cell imbalances caused by uneven light intensity across multiple PV arrays. The proposed DC-AC-AC converter naturally addresses the per-phase imbalance via its three-phase medium-frequency AC link. However, in instances where light intensity disturbances affected the k PV arrays unevenly, it resulted in varying energy harvest levels from each array, leading to per-cell imbalance. In conclusion, both reduced-scale versions validated the core concept of the converter, suggesting that the complete topology would function effectively.

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