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ADVANCED SOLAR GRID INTEGRATION SOLUTION USING A HIGH- EFFICIENCY COUPLED INDUCTOR MULTIPORT CONVERTER FOR OPTIMIZED POWER DELIVER

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ABSTRACT

The increasing global focus on renewable energy, particularly solar power, highlights the urgent need for advanced solutions that enhance energy integration and distribution. Traditional power delivery systems often struggle to accommodate multiple energy inputs, resulting in inefficiencies and higher operational costs. This paper proposes an advanced solar grid integration solution utilizing a high-efficiency coupled inductor multiport converter. Designed to optimize power delivery, the system enhances the performance of photovoltaic (PV) systems by efficiently managing power flow and improving grid integration. At the core of this solution is the coupled inductor multiport converter, which enables effective power distribution among multiple input sources and the grid, ensuring minimal losses and maximum efficiency. A three-phase voltage source inverter (VSI) is employed to convert DC power from the PV system into high-quality AC power suitable for grid integration. To ensure a smooth and stable power supply, the VSI is integrated with an LC filter, which eliminates harmonics and improves power quality. The PWM generator controls the VSI by adjusting the duty cycle to regulate voltage and current, optimizing power output based on real-time conditions. Additionally, a PI controller is implemented to fine-tune the PWM signals, ensuring rapid and precise responses to fluctuations in load and power generation. This contributes to maintaining grid stability and overall system efficiency.

Keywords: grid, solar, multiport converter

I. INTRODUCTION

The transition to renewable energy has accelerated in recent years due to the urgent need to mitigate climate change, enhance energy security, and promote sustainable development. Among the most promising renewable energy sources, solar power stands out for its widespread availability and cost-effectiveness. However, integrating solar energy into existing power grids presents challenges related to sustainability, efficiency, and reliability. Addressing these challenges requires advanced solar grid integration solutions. One such innovative approach is the use of a high-efficiency coupled inductor multiport converter (CIMPC) designed for optimized power delivery. As photovoltaic (PV) systems continue to expand within the energy landscape, advanced power electronics are essential for managing the variability and intermittency of solar power generation. Traditional power converters often struggle to meet the demands of modern grids, which require fast response times, high conversion efficiency, and the ability to interface with multiple energy sources and storage systems. The CIMPC architecture overcomes these limitations by offering multiple input and output ports, enabling seamless integration of solar energy with other power sources such as wind and battery storage. This enhances overall system flexibility and reliability.

At the core of the CIMPC is its ability to optimize power delivery through advanced control strategies and high-efficiency inductive coupling. This architecture facilitates the efficient transferof energy from Guanhong Song et al. (2022) explored strategies to reduce greenhouse gas emissions, highlighting the growing integration of renewable energy into electrical grids. Since inverters serve as critical links between grids and distributed energy resources, they have become essential components of modern power networks. Recent studies indicate that the Synchronous Reference Frame Phase-Locked Loop (SRF-PLL) shares fundamental structural elements, distinct filtering characteristics, and frequency flexibility with most three-phase and single-phase PLLs. Inverters that actively regulate grid frequency and voltage contribute to overall power system stability by providing synchronizing power, inertial response, and damping mechanisms. Grid-forming inverters, which operate

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in islanded mode, play a key role in system restoration, acting as black-start resources capable of re-energizing the grid after a total blackout. As the grid shifts toward increased renewable energy penetration, grid-forming inverters are replacing traditional synchronous generators, reducing reliance on fossil fuel-based power generation. However, the control algorithms required for grid-forming inverters are significantly more complex than those used in conventional grid-following inverters, leading to challenges in implementation and tuning. Poor design, improper parameterization, or unfavorable interactions with other grid components can lead to system instability when deploying grid-forming inverters.

Seung-Jin Yoon et al. (2022) introduced a grid voltage sensorless current controller designed to enhance stability and reduce harmonics for grid-connected inverters in weak grid conditions. Inductive Capacitive-Inductive (ICL) filters, which introduce higher-order dynamics, require precise resonance frequency damping to mitigate resonance-related issues. When a grid-connected inverter is linked to a weak grid with unknown impedance and distorted harmonics, the resonance effect of the LCL filter significantly impacts current quality. While additional sensors can improve monitoring and control, they also raise concerns regarding increased system costs and hardware complexity. A voltage sensorless approach eliminates the need for voltage sensors, thereby reducing both system complexity and cost. This method effectively suppresses grid harmonics, even under weak grid conditions, by leveraging advanced control techniques such as resonant controllers and harmonic compensators. Additionally, the voltage sensorless controller adaptively adjusts its parameters in response to variations in grid impedance, ensuring stable and reliable operation across different grid conditions. However, depending on the control strategy, the sensorless controller may have limited capabilities in suppressing low-frequency grid harmonics, which can still affect the power quality of the grid-connected inverter.

Chuanyue Li et al. (2022) examined the stability challenges associated with Phase-Locked Loop (PLL)-based vector control voltage source inverters (VSIs) when connected to very weak AC grids. Traditional inductive grid impedance adjustment stabilizes this connection by effectively reducing grid impedance. Enhancing grid impedance compensation through the PLL significantly improves VSI stability and performance in weak grid conditions, where grid impedance is high and fluctuates considerably. The implementation of grid impedance compensation mechanisms allows the PLL to dynamically adapt to grid variations, ensuring consistent and reliable VSI operation under diverse conditions. However, this enhanced compensation requires more complex signal processing and control algorithms, increasing the overall complexity of the VSI control system. Consequently, advanced hardware or more powerful microprocessors may be necessary to handle these computational demands. Despite its advantages, grid impedance compensation does not entirely eliminate the risk of instability, particularly if compensation algorithms are not precisely tuned or if grid impedance fluctuates rapidly.

II. DC-DC CONVERTERS

In response to the global energy crisis and the greenhouse effect caused by excessive fossil fuel consumption, environmentally friendly renewable energy sources are increasingly being utilized as backup power solutions. However, photovoltaic (PV) energy systems face challenges such as power degradation due to mismatches between PV panels, which fluctuate based on environmental conditions. To ensure a stable power supply, PV energy conversion systems typically integrate PV sources with a battery storage system (BSS). In hybrid energy systems, each energy source is usually connected to the DC bus via a separate DC–DC converter. However, this structure has significant drawbacks, including high costs due to multiple components and reduced efficiency caused by multiple conversion stages. To address these issues, multiport converters (MPCs) have been extensively researched and are gaining increasing attention as a viable solution. MPCs offer several advantages over multiple single-input DC–DC converters in renewable energy systems. These include fewer conversion stages, higher power density, improved system efficiency, and centralized control for unified power management across multiple ports. MPCs are generally classified into two categories: non-isolated and isolated MPCs. Isolated MPCs, often built using full-bridge or half-bridge topologies with transformers, provide galvanic isolation and enhanced voltage gain. However, they also introduce additional costs and energy losses. In contrast, non-isolated MPCs offer higher power density, greater efficiency, and lower manufacturing costs, making them more suitable for medium- and low-power applications.

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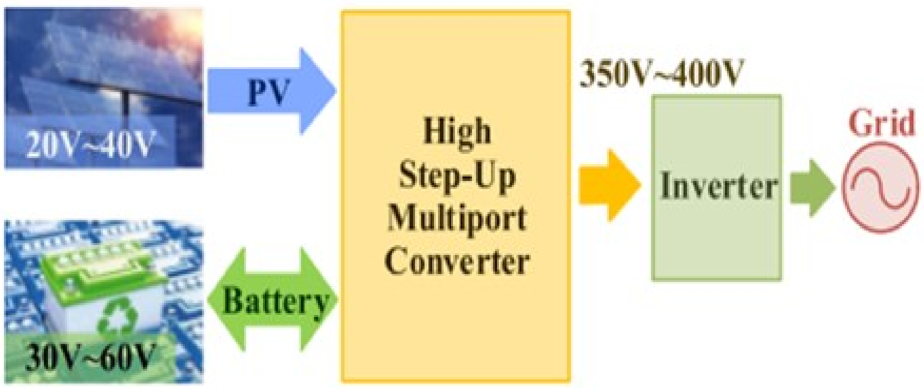

Figure 1. Block Diagram of conventional DC-DC converter

This system introduces a novel structure based on a no-isolated high-step-up multiport converter (MPC). The proposed MPC offers high voltage gain and low normalized peak inverse voltage across semiconductor devices. A maximum power point tracking (MPPT) algorithm is implemented for each photovoltaic (PV) input source, effectively mitigating mismatches among PV modules. Unlike conventional extendable MPCs, this design extends unidirectional input ports and bidirectional ports to accommodate a wider range of renewable energy sources and energy storage devices. Additional benefits include continuous input currents and modularity. This work explores various operating modes, steady-state analysis, and design considerations.

III. PROPOSED MULTIPORT CONVERTER

The increasing adoption of electric vehicles (EVs) has highlighted the need for efficient charging facilities, especially for long-distance travel. Multiport charging and renewable energy-based charging stations address two major challenges in EV technology: power consumption and charging time. Integrating a photovoltaic (PV) system enhances the reliability of charging station operations. However, without grid connectivity through power converters, the PV source alone cannot fully meet the load requirements. Charging stations utilizing multiple energy sources require separate converters to regulate the DC bus (PV and battery) and the AC bus (grid), increasing costs and complexity. Bidirectional dual active bridge (DAB) converters enable Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) charging by employing phase-shift modulation for voltage conversion. For PV-grid-tied integration, the Z-source inverter (ZSI) is a more suitable option, as conventional voltage source inverters (VSIs) and current source inverters (CSIs) cannot perform simultaneous boost and buck operations. In contrast, the ZSI utilizes inductors and capacitors to achieve both operations concurrently. Selecting an appropriate impedance network ensures optimal steady-state performance for PV-grid integration, while properly chosen inductors and capacitors minimize voltage ripples at the load terminal. Current ZSI topologies do not support multiport charging, but an improved design should allow seamless switching between single-port and multiport charging alongside PV-grid integration. This work enhances the existing Z-source network by introducing multiple charging ports and optimizing PV-grid-tied operation. Achieving these features requires additional switches in the converter architecture. In microgrid applications, the non-isolated boost converter facilitates efficient power flow between AC and DC buses with fewer switches. Additionally, incorporating a coupled inductor recycles energy lost through the capacitor, resulting in higher voltage output and improved voltage gain.

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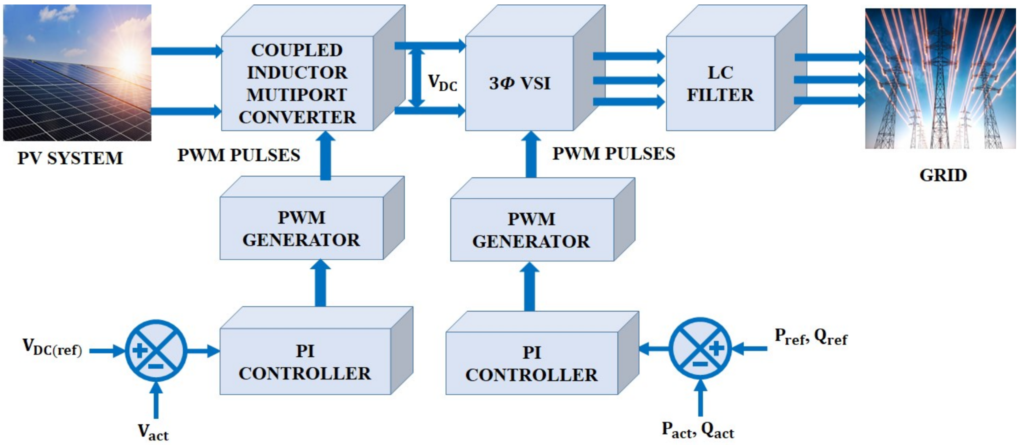

Figure 2. Block Diagram of Proposed System

This paper proposes an advanced solar grid integration solution utilizing a high-efficiency coupled inductor multiport converter. The system is designed to enhance the performance of photovoltaic (PV) systems by efficiently managing power flow and improving grid integration. At its core, the coupled inductor multiport converter facilitates effective power distribution among multiple input sources and the grid, minimizing energy losses and maximizing overall efficiency. The direct current (DC) generated by the PV system is converted into high-quality alternating current (AC) for seamless grid integration using a three-phase voltage source inverter (VSI). To ensure a stable and clean power supply, an LC filter is incorporated with the VSI, reducing harmonics and enhancing grid stability. The pulse width modulation (PWM) generator dynamically regulates the VSI by adjusting the duty cycle, thereby controlling voltage and current levels in real time. Additionally, a proportional-integral (PI) controller fine-tunes the system's performance by modifying PWM signals, ensuring a fast and accurate response to fluctuations in load and power generation. This approach helps maintain grid stability and efficiency. The proposed methodology is implemented using MATLAB Simulation 2021a, enabling precise modeling and analysis of the system's components and performance.

IV. RESULTS AND DISCUSSIONS

MATLAB, short for Matrix Laboratory, is a powerful programming environment and high-performance computing platform designed for solving mathematical and engineering problems. Developed by MathWorks, MATLAB seamlessly integrates computation, visualization, and programming within a user-friendly interface, making it one of the most versatile tools for simulation and modeling across various industries. This section explores MATLAB's significance in simulation, highlighting its key features and wide range of application.

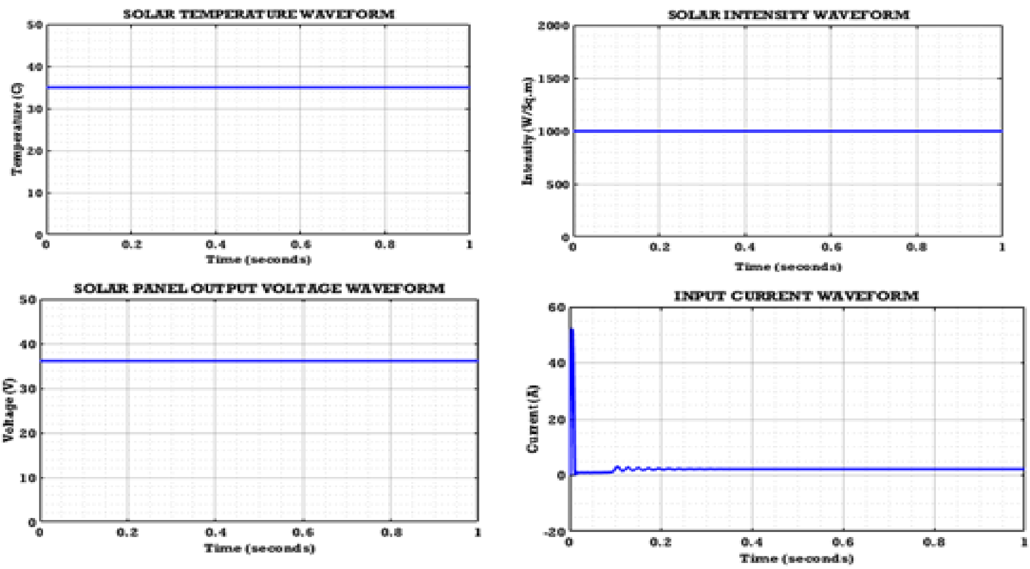

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Figure 3. Input Waveform

The relationship between temperature, solar intensity, output voltage, and input current over time. The temperature remains constant at 25°C, while solar intensity stays steady at approximately 1000 W/m². The output voltage remains around 10 V, while the input current fluctuates before stabilizing at approximately 40 A. Figure 3 shows the input waveforms and figure 4 depicts the output waveforms.

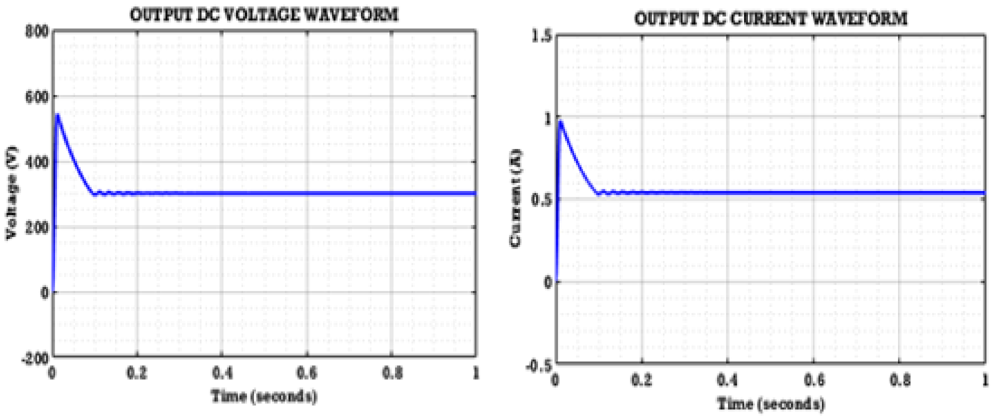

Figure 4. Output Waveform

The output DC voltage and current waveforms over time show a transient response in the system. The output voltage rapidly drops to approximately 600 V before stabilizing, while the output current quickly decreases to around 0 A. These values highlight the system's dynamic behavior during the specified time interval.

V. CONCLUSION

In conclusion, this advanced solar grid integration solution effectively enhances the performance of photovoltaic (PV) systems by utilizing a coupled inductor multiport converter. The system optimizes power delivery by enabling efficient power distribution across multiple energy sources while minimizing losses. The integration of a three-phase voltage source inverter (VSI) and an LC filter ensures the generation of high-quality AC power, while the PWM generator and PI controller work together to maintain stable and efficient operation. This adaptive control mechanism allows the system to quickly respond to changes in load and generation, thus supporting grid stability. The implementation of this project using MATLAB Simulation 2021 further validates its feasibility and effectiveness. Overall, the proposed solution not only boosts the efficiency of solar energy systems but also contributes to a reliable and sustainable power supply for grid integration.

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