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Development and Performance Analysis of a Battery-less Hybrid PV–Fuel Cell System for Island Electrification

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ABSTRACT

The increasing global demand for energy and the rapid depletion of fossil fuel resources have driven the need for sustainable and reliable power generation solutions. In Bangladesh, particularly in remote island and coastal regions, extending the national grid remains technically challenging and economically unfeasible. Although renewable energy systems provide a promising alternative, conventional configurations heavily depend on battery storage, which increases overall system cost, maintenance requirements, and environmental concerns. To overcome these limitations, this study proposes a battery-less hybrid renewable energy system integrating solar photovoltaic (PV) and hydrogen fuel cell technologies to ensure continuous power supply. In the proposed configuration, the solar PV system operates as the primary energy source during daylight hours, while the fuel cell system provides backup power during periods of low or no solar irradiation, thereby enabling uninterrupted 24-hour operation. The system incorporates a transformer-coupled push–pull inverter for efficient DC–AC conversion, followed by an LCL filter to reduce harmonic distortion and improve output waveform quality. A matrix converter is further employed to convert single-phase AC into three-phase AC, enhancing compatibility with practical load and grid applications. The overall system is modeled and analyzed using MATLAB/Simulink to evaluate its performance. Simulation results demonstrate stable voltage output, effective harmonic reduction, and high system efficiency, confirming the feasibility of the proposed approach. The battery-less configuration significantly reduces system cost and complexity, making it a viable and sustainable solution for electrification in remote island areas of Bangladesh.

INTRODUCTION

The rapid growth in global energy demand, coupled with the depletion of fossil fuel resources, has intensified the need for sustainable and reliable energy solutions. In developing countries such as Bangladesh, ensuring an uninterrupted electricity supply remains a significant challenge, particularly in remote islands and coastal regions where grid extension is technically complex and economically infeasible. Although Bangladesh has made notable progress in power generation, many isolated areas still suffer from unreliable electricity access, often relying on costly and environmentally harmful diesel generators. Renewable energy, especially solar photovoltaic (PV) systems, has emerged as a promising alternative due to the country's high solar irradiance potential.

However, standalone PV systems are inherently intermittent and unable to provide continuous power, particularly during nighttime or low irradiation conditions. Conventional solutions rely heavily on battery storage, which significantly increases system cost, maintenance requirements, and environmental concerns. Recent studies indicate that battery systems can contribute significantly to overall system cost, making them less attractive for large-scale deployment. Consequently, hybrid renewable energy systems integrating complementary sources such as fuel cells have gained considerable attention for improving reliability and reducing dependency on battery storage.

In hybrid PV–fuel cell systems, solar energy serves as the primary source during daytime, while fuel cells operate as backup sources during periods of insufficient solar generation, thereby ensuring continuous power supply. Previous research has demonstrated that such hybridization improves system stability, enhances power quality, and reduces voltage fluctuations compared to standalone systems. Moreover, efficient inverter design plays a crucial role in maintaining grid compatibility and minimizing harmonic distortion. Transformer-coupled push–pull inverters have been identified as suitable candidates due to their voltage boosting capability, electrical isolation, and improved efficiency.

Power quality improvement is a major concern in inverter-based renewable systems. LCL filters are widely adopted for harmonic mitigation, providing superior performance compared to conventional filtering techniques and significantly reducing Total Harmonic Distortion (THD) . In addition, recent advancements in power conversion technologies, such as matrix converters, enhance system flexibility by enabling direct AC–AC conversion and facilitating three-phase power generation without intermediate DC links.

Furthermore, modern energy management strategies and techno-economic analyses have demonstrated that hybrid PV–fuel cell systems can achieve improved operational efficiency and long-term economic viability.

These developments indicate that battery-less hybrid

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configurations can offer a cost-effective and sustainable solution for decentralized electrification. However, despite these advancements, limited research has focused on battery-less hybrid PV–fuel cell systems specifically designed for island electrification in Bangladesh.

Therefore, this study proposes a battery-less hybrid renewable energy system integrating solar PV and hydrogen fuel cell technologies to ensure continuous and reliable power supply. The proposed system incorporates a transformer-coupled push–pull inverter, LCL filter, and matrix converter to enhance power quality, efficiency, and grid compatibility. This approach aims to provide a sustainable and economically viable solution for remote island regions, contributing to long-term energy security and environmental sustainability.

LITERATURE REVIEW

Hybrid renewable energy systems have been extensively studied due to their potential to provide reliable and continuous power supply by combining complementary energy sources. In particular, the integration of solar photovoltaic (PV) systems with fuel cell technologies has been recognized as an effective approach to overcome the intermittency of solar energy. Previous studies have demonstrated that fuel cells can supply power during periods of low solar irradiation, thereby improving system stability and ensuring uninterrupted energy delivery (Rajkumar, 2018; Remache *et al.*, 2024).

The effectiveness of hybrid systems largely depends on efficient power conversion and control mechanisms. Research on grid-connected fuel cell inverter systems highlights the importance of stable DC–AC conversion and synchronization for reducing harmonic distortion and improving overall efficiency (Ramy *et al.*, 2016). In this context, transformer-coupled push–pull inverter topologies have gained attention due to their ability to provide voltage boosting, electrical isolation, and improved conversion efficiency, making them suitable for renewable energy applications (Haque *et al.*, n.d.).

Power quality is another critical factor in renewable energy systems. Studies have shown that LCL filters are more effective than conventional LC filters in attenuating high-frequency harmonics, thereby reducing Total Harmonic Distortion (THD) and improving output waveform quality (Hamza *et al.*, 2015). Furthermore, matrix converters have been introduced as an efficient solution for direct AC–AC conversion, enabling the generation of balanced three-phase output without the need for intermediate DC-link components, which enhances system compactness and operational efficiency (Haque *et al.*, n.d.).

Recent advancements in hybrid system design have focused on energy management and optimization strategies to improve system performance. Comprehensive studies have emphasized the importance of coordinated control between multiple energy sources to enhance efficiency and ensure reliable operation under varying load conditions (Sadeghian *et al.*, 2025; Guo *et al.*, 2025). In addition, renewable-centric energy management frameworks in hydrogen-based microgrids have demonstrated improved scheduling efficiency and sustainability outcomes, further strengthening the applicability of hybrid energy systems (Kerama, 2025). Techno-economic analyses have also confirmed that hybrid PV–fuel cell systems are cost-effective and suitable for off-grid and remote applications, particularly in developing regions (Hossain *et al.*, 2021). Advanced inverter configurations, including multilevel and grid-tied systems, have been shown to improve power quality and grid compatibility (Muftah *et al.*, 2022). Moreover, recent studies on renewable energy development in Bangladesh highlight the environmental benefits and future potential of sustainable energy systems, emphasizing the importance of adopting clean and reliable energy solutions in remote and underserved regions (Islam, 2025). Despite these advancements, limited research has focused on battery-less hybrid PV–fuel cell systems specifically designed for island electrification in Bangladesh. Given the challenges associated with grid extension and the high cost of battery storage, there is a need for innovative system configurations that ensure continuous power supply while maintaining cost-effectiveness and operational reliability (Rahim & Hosam-E-Haider, 2015). This research addresses this gap by proposing a battery-less hybrid renewable energy system tailored for remote island applications.

MATERIALS AND METHODS

The proposed battery-less hybrid renewable energy system is designed and simulated using MATLAB Simulink to ensure continuous and reliable power generation. The overall system follows a structured energy conversion process, starting from renewable DC generation and ending with three-phase AC output suitable for load or grid integration. The system architecture consists of solar photovoltaic (PV) and hydrogen fuel cell sources, a transformer-coupled push–pull inverter, an LCL filter, and a matrix converter.

Initially, two complementary DC sources are employed: a solar PV system and a Proton Exchange Membrane (PEM) fuel cell. The PV system converts solar irradiance into DC power during daylight hours, while the fuel cell provides backup power during low or no solar conditions through electrochemical conversion of hydrogen and oxygen. Both subsystems are modeled independently to ensure stable voltage and current characteristics before integration . This modular approach enhances system reliability and enables continuous 24-hour operation without battery storage.

The generated DC power is then converted into single-phase AC using a transformer-coupled push–pull inverter. This topology is selected due to its voltage boosting capability, electrical isolation, and efficient DC–AC conversion. Pulse Width Modulation (PWM) is applied to control switching operations and generate a stable AC waveform. However, the inverter output contains high-frequency switching harmonics, which are mitigated using an LCL filter. The LCL filter, consisting of two inductors and a shunt capacitor, effectively reduces Total Harmonic Distortion (THD) and improves output waveform quality. Following harmonic filtering, the single-phase AC output is converted into three-phase AC using a matrix converter. This stage enables direct AC–AC conversion without requiring an intermediate DC link, resulting in improved efficiency and reduced system complexity. The matrix converter generates balanced three-phase voltages with 120° phase displacement, making the system suitable for industrial loads and grid applications. To further enhance power quality, a three-phase LCL filter is incorporated at the output stage to suppress residual harmonics and ensure stable sinusoidal waveforms.

The performance of the system is evaluated through simulation by analyzing voltage stability, current characteristics, harmonic distortion, and efficiency under different operating conditions. This structured methodology ensures accurate modeling, modular implementation, and reliable performance assessment of the proposed hybrid renewable energy system.

The overall architecture of the proposed battery-less hybrid renewable energy system is illustrated in Fig. 1. The system integrates solar PV and fuel cell sources to generate DC power, which is converted into single-phase AC using a push–pull inverter, filtered through an LCL filter, and further converted into three-phase AC using a matrix converter for practical load and grid applications.

RESULTS AND DISCUSSION

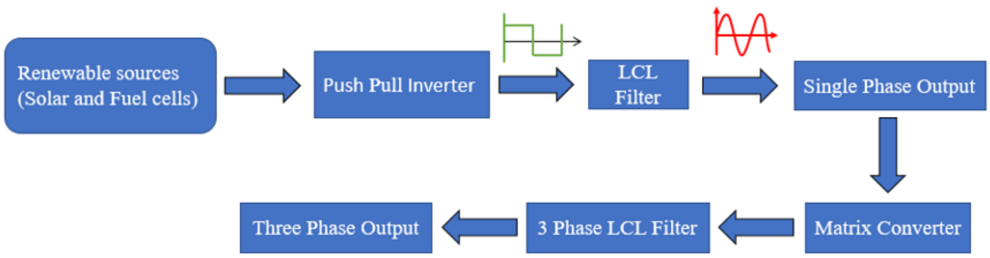

Figure 1: Block diagram of the proposed battery-less hybrid PV–fuel cell renewable energy system

The performance of the proposed battery-less hybrid renewable energy system was evaluated using MATLAB/Simulink simulations. The system integrates solar photovoltaic (PV) and fuel cell sources with a push–pull inverter, LCL filters, and a matrix converter to achieve continuous and stable power output. The simulation analysis focuses on voltage characteristics, harmonic reduction, efficiency, and three-phase power generation capability.

Solar PV Simulation Results and Performance Analysis

In this study, the system performance is initially evaluated under solar-powered operation for both single-phase and three-phase output configurations. The analysis is structured in this manner because single-phase supply is predominantly required for residential and small-scale applications in remote island regions of Bangladesh, where most electrical loads consist of lighting, household appliances, and low-power devices. In contrast, three-phase power is comparatively less common in such areas and is mainly associated with specific applications such as small industries, irrigation systems, or community-level infrastructure. The solar-powered module is primarily designed to operate during daylight hours, utilizing available solar irradiance as the main energy source for power generation. Therefore, the primary focus is placed on validating the single-phase output performance to ensure reliable and efficient operation under typical load conditions. Subsequently, the system is extended to three-phase operation to demonstrate its capability for broader applicability and future scalability. This dual-level evaluation confirms that the proposed hybrid renewable energy system can effectively meet both present and potential energy demands in island regions, ensuring flexibility, reliability, and practical usability.

Single-Phase Performance Analysis of the Solar PV System under Simulation

Figure. 2 presents the MATLAB/Simulink model of the solar PV-based single-phase power conversion stage, incorporating a transformer-coupled push–pull inverter and an LCL filter for waveform conditioning. The simulation is carried out under standard operating conditions with an irradiance of 1000 W/m² and a temperature of 25°C. The obtained results demonstrate that the system produces a stable output voltage of approximately 218 V RMS and an output current of about 5.32 A at an optimal load resistance of 41 Ω. The overall conversion efficiency is found to be around 96.6%, indicating high performance of the inverter and filtering stages. Furthermore, the LCL filter effectively suppresses switching harmonics, resulting in a smooth and near-sinusoidal output waveform. These results confirm the capability of the proposed configuration to deliver stable and efficient single-phase AC power suitable for practical residential applications

Figure 3 illustrates the simulated single-phase output voltage and current waveforms obtained from the proposed solar PV-based system after DC–AC conversion and LCL filtering. The output voltage waveform exhibits a stable sinusoidal pattern with a peak corresponding

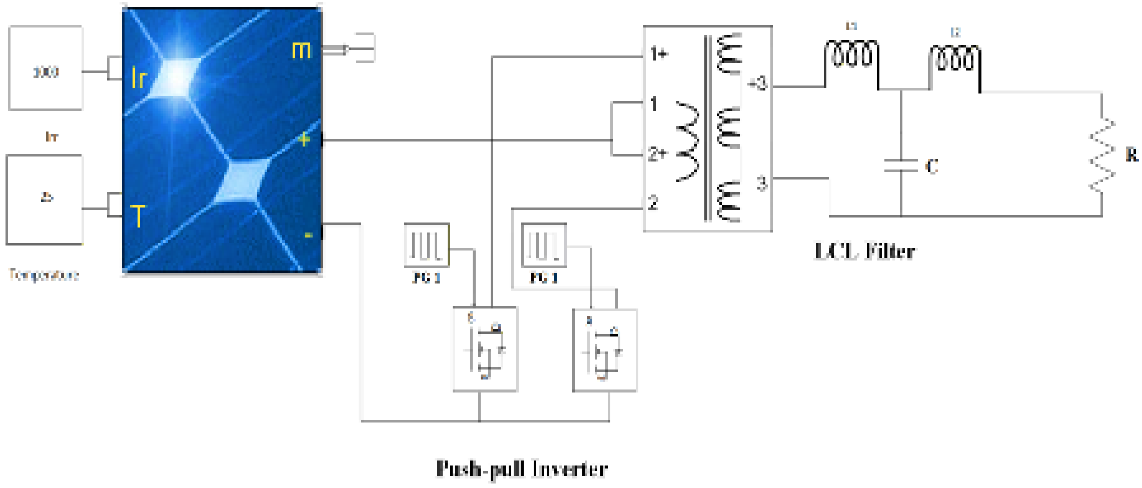

Figure 2: MATLAB/Simulink model of solar PV-based single-phase system with push–pull inverter and LCL filter

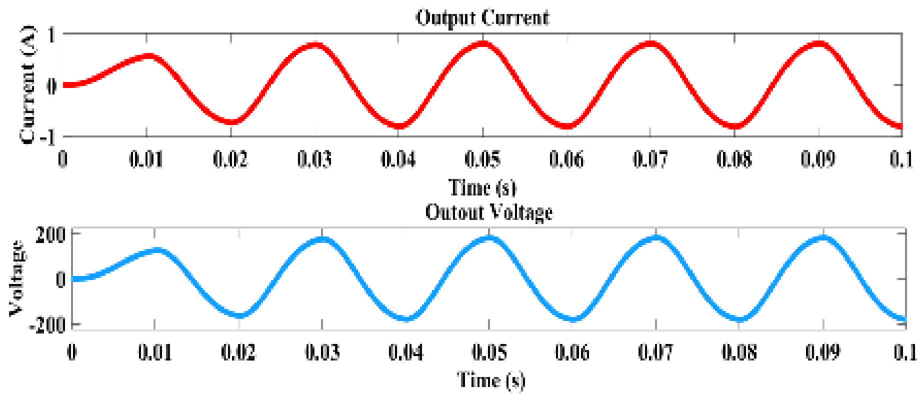

Figure 3: Simulated single-phase output voltage and current waveforms

to approximately 218 V RMS, maintaining a constant frequency of 50 Hz. Similarly, the output current waveform follows a sinusoidal profile and remains in phase with the voltage, indicating a predominantly resistive load condition and near-unity power factor operation.

The smooth and continuous nature of both voltage and current waveforms confirms the effective suppression of high-frequency switching harmonics by the LCL filter. Additionally, the absence of noticeable distortion demonstrates the capability of the push–pull inverter and filtering stage to produce high-quality AC output. These results validate that the proposed system can deliver stable and reliable single-phase power, making it suitable for residential applications in remote areas.

Single-Phase Performance Analysis of the Solar PV System under Simulation

Figure 4 illustrates the MATLAB/Simulink model of the solar PV-based three-phase power conversion system, which integrates a transformer-coupled push–pull inverter, LCL filter, matrix converter, and a three-phase LCL filter. The solar PV module generates DC power under standard operating conditions, which is first converted into single-phase AC using the push–pull inverter. The output is then passed through an LCL filter to reduce switching harmonics and improve waveform quality before being supplied to the matrix converter. The matrix converter plays a crucial role in converting the filtered single-phase AC into balanced three-phase AC output without the need for an intermediate DC link. This conversion is achieved through controlled switching, ensuring proper phase displacement and voltage regulation. To further enhance the quality of the output, a three-phase LCL filter is incorporated, which effectively suppresses residual harmonics and ensures smooth sinusoidal waveforms across all three phases. The overall simulation confirms that the system is capable of producing stable and balanced three-phase voltage and current outputs suitable for practical applications. The integration of filtering and conversion stages ensures improved power quality, reduced harmonic distortion, and reliable operation, demonstrating the effectiveness of the proposed configuration for island electrification and grid-compatible power delivery.

Figure 5 illustrates the simulated three-phase output voltage and current waveforms obtained from the proposed solar PV-based system after matrix conversion

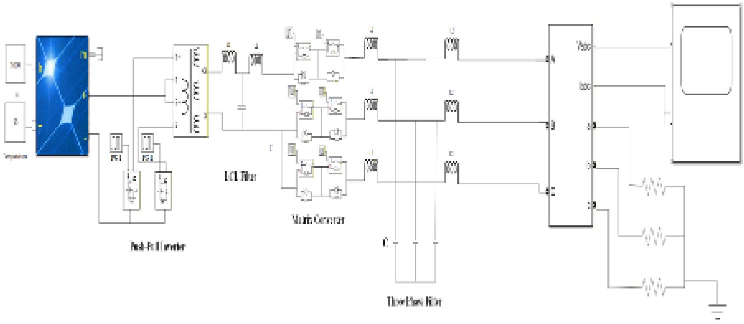

Figure 4: MATLAB/Simulink model of the solar PV-based three-phase system incorporating a push–pull inverter, LCL filter, matrix converter, and three-phase LCL filter

and three-phase LCL filtering. The output voltages exhibit balanced sinusoidal waveforms with equal amplitude and a phase displacement of 120° between each phase, confirming proper three-phase generation. The RMS voltage of each phase is maintained at approximately 220 V, with a constant operating frequency of 50 Hz.

Similarly, the output currents are sinusoidal and balanced across all three phases, following the corresponding voltage waveforms with consistent phase relationships. The smooth and continuous nature of both voltage and current waveforms indicates effective suppression of switching harmonics by the three-phase LCL filter. The balanced condition also ensures minimal neutral current and efficient power delivery.

These results validate the capability of the matrix converter and filtering stages to produce high-quality three-phase power. The system demonstrates stable operation, improved power quality, and reliable performance, making it suitable for industrial loads and grid-connected applications in remote island regions.

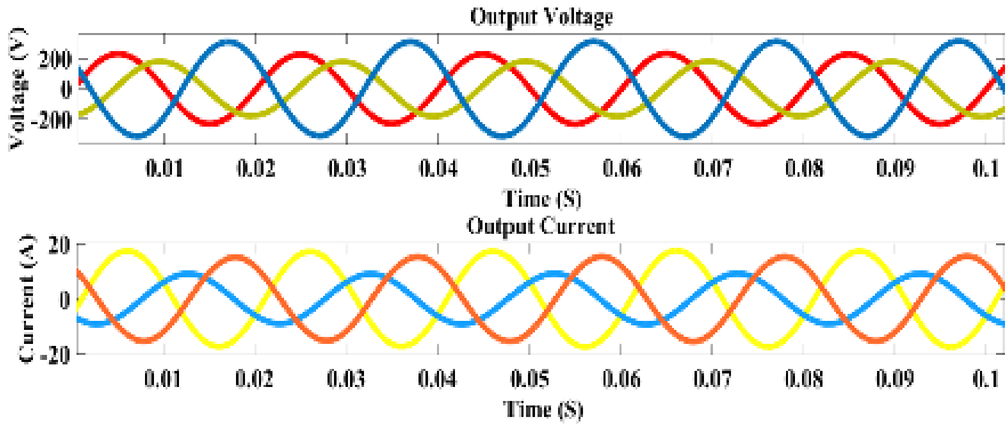

Figure 5: Simulated three-phase output voltage and current waveforms

Fuel cell Simulation Results and Performance Analysis

The performance of the fuel cell subsystem is evaluated through MATLAB/Simulink simulation to assess its role as a reliable secondary energy source in the proposed hybrid system. The Proton Exchange Membrane (PEM) fuel cell generates DC power through an electrochemical reaction between hydrogen and oxygen, ensuring continuous energy supply during periods of low or no solar irradiation. In this system, the fuel cell is primarily incorporated for redundancy purposes, operating as a backup source when solar generation is unavailable, such as during nighttime or unfavorable weather conditions. This complementary operation enhances overall system reliability and ensures uninterrupted power supply. The generated DC output is converted into AC using a transformer-coupled push–pull inverter followed by an LCL filter to improve waveform quality. Simulation results demonstrate that the fuel cell system produces stable and continuous single-phase AC output with consistent voltage and frequency characteristics. The filtered waveform is nearly sinusoidal, indicating effective harmonic suppression. Furthermore, the output is processed through a matrix converter to generate balanced three-phase AC power with proper phase displacement and stable operation. Unlike solar PV generation, the fuel cell operates independently of environmental conditions, making it a dependable source for continuous power delivery. The results confirm that the fuel cell subsystem effectively complements the solar PV system, ensuring uninterrupted operation and improving the overall robustness and reliability of the proposed battery-less hybrid renewable energy system.

Fuel Cell Simulation Results and Performance Analysis for Single-Phase Output

Figure 6 illustrates the MATLAB/Simulink model of the fuel cell-based single-phase power conversion system, where a Proton Exchange Membrane (PEM) fuel cell is employed as the DC power source. The fuel cell generates electrical energy through the electrochemical reaction between hydrogen and oxygen, providing a continuous and stable DC output independent of solar availability. This DC power is subsequently converted into single-phase AC using a transformer-coupled push–pull inverter, followed by an LCL filter to improve waveform quality.

The simulation results demonstrate that the system produces a stable single-phase AC output with consistent voltage regulation and continuous power delivery. The inverter effectively converts DC to AC, while the LCL filter suppresses switching harmonics, resulting in a smooth and near-sinusoidal waveform. These results confirm that the fuel cell subsystem can reliably operate as a backup source, ensuring uninterrupted power supply during non-daylight periods and enhancing the overall robustness of the proposed hybrid renewable energy system.

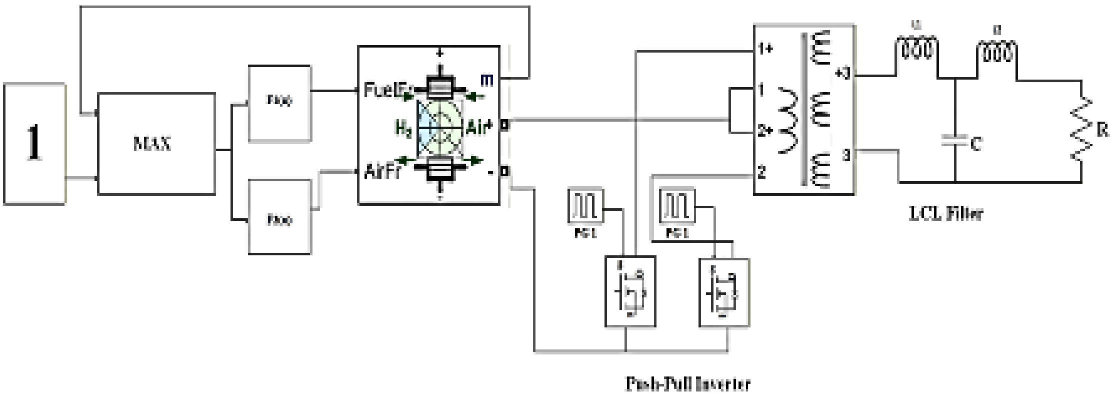

Figure 6: MATLAB/Simulink model of the fuel cell-based single-phase power conversion system

Figure 7 illustrates the simulated single-phase output voltage and current waveforms obtained from the fuel cell-based power conversion system. The fuel cell generates a stable DC output, which is converted into AC using a transformer-coupled push–pull inverter and subsequently filtered through an LCL filter to improve waveform quality. The resulting output voltage waveform exhibits a smooth sinusoidal profile with an RMS value close to the desired operating level and a constant frequency of 50 Hz.

The corresponding output current waveform also follows a sinusoidal pattern and remains in phase with the voltage, indicating stable operation under a resistive load condition and near-unity power factor. The absence of significant distortion in both voltage and current waveforms confirms the effectiveness of the LCL filter in suppressing switching harmonics generated by the inverter. Furthermore, the continuous and stable nature of the output demonstrates the capability of the fuel cell system to provide reliable power during non-daylight periods. These results validate the role of the fuel cell subsystem as an effective backup source, ensuring uninterrupted single-phase power delivery in the proposed hybrid renewable energy system.

Fuel Cell Simulation Results and Performance Analysis for Single-Phase Output

Figure 8 illustrates the MATLAB/Simulink model of the fuel cell-based three-phase power conversion system. In this configuration, a Proton Exchange Membrane (PEM) fuel cell serves as the primary DC power source, generating electricity through the electrochemical reaction between hydrogen and oxygen. The fuel cell is primarily utilized during non-daylight periods or when solar power is unavailable, ensuring continuous and reliable system operation.

The generated DC output is first converted into single-phase AC using a transformer-coupled push–pull inverter, followed by an LCL filter to suppress switching harmonics and improve waveform quality. The filtered single-phase AC is then fed into a matrix converter, which performs direct AC–AC conversion to produce balanced three-phase output without the need for an intermediate DC link. A three-phase LCL filter is incorporated at the output stage to further reduce harmonic distortion and ensure smooth sinusoidal waveforms.

The simulation model demonstrates that the system is capable of generating stable and balanced three-phase voltage and current outputs with proper phase displacement and frequency regulation. These results confirm the effectiveness of the fuel cell subsystem in supporting three-phase power generation, ensuring uninterrupted energy supply, and enhancing the overall reliability and performance of the proposed battery-less hybrid renewable energy system.

Figure 9 illustrates the simulated three-phase output voltage and current waveforms obtained from the fuel cell-based power conversion system. The output voltages exhibit balanced sinusoidal waveforms with equal

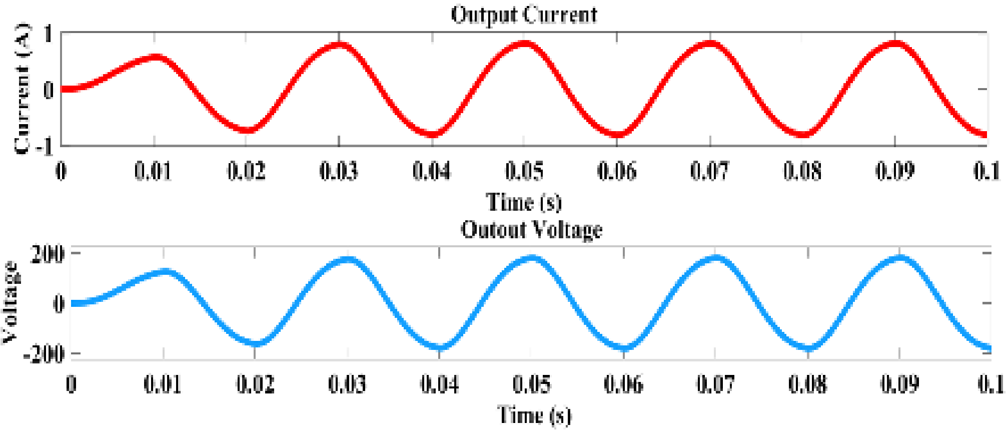

Figure 7: Simulated single-phase output voltage and current waveforms of the fuel cell system

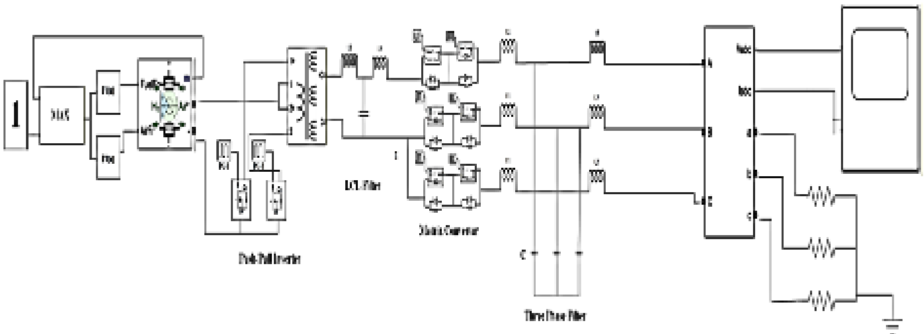

Figure 8: MATLAB/Simulink model of fuel cell-based three-phase power conversion system with matrix converter and LCL filters

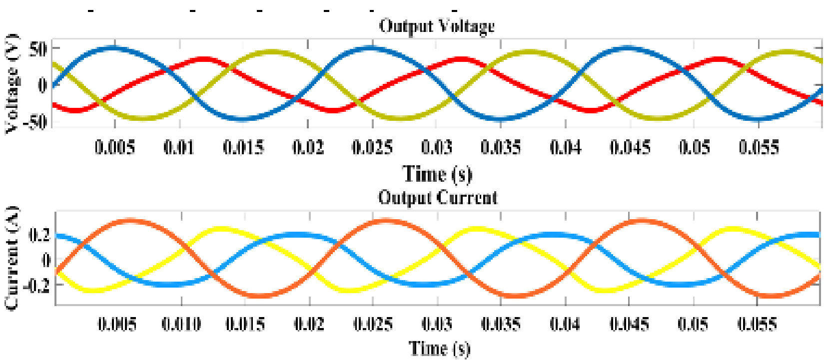

Figure 9: Simulated three-phase output voltage and current waveforms of the fuel cell system

amplitude and a phase displacement of 120° between each phase, confirming proper three-phase generation. The system maintains a stable operating frequency of 50 Hz, ensuring compatibility with standard grid and industrial load requirements.

The corresponding output currents also follow sinusoidal patterns and remain balanced across all three phases, indicating stable system operation and effective load sharing. The smooth and continuous nature of the voltage and current waveforms demonstrates the effectiveness of the matrix converter and three-phase LCL filter in minimizing harmonic distortion and improving power quality. Additionally, the absence of significant waveform distortion confirms efficient DC–AC–AC conversion from the fuel cell source.

These results validate the capability of the fuel cell subsystem to deliver stable and reliable three-phase power during non-daylight conditions. The system ensures continuous operation, balanced output, and improved power quality, making it suitable for both residential and industrial applications in remote island regions.

Efficiency Analysis of the Proposed System under Varying Load Conditions

The efficiency performance of the proposed battery-less hybrid renewable energy system is evaluated under different load resistance conditions to identify its optimal operating range. As illustrated in Figure 10 the

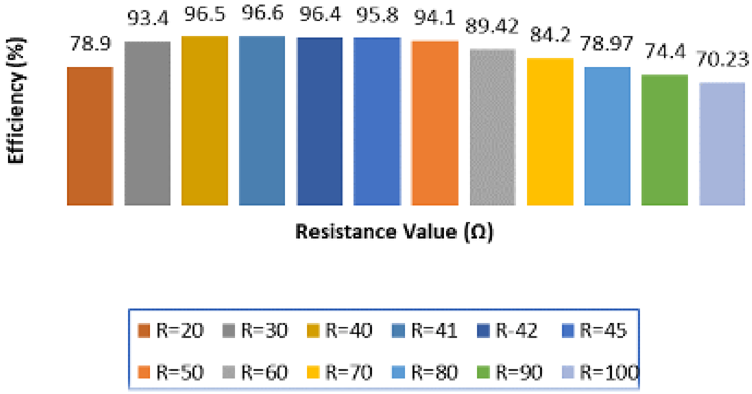

Figure 10: Efficiency variation of the proposed system with respect to load resistance under solar PV operation

system exhibits a clear dependence of efficiency on load variation, particularly under single-phase solar PV operation, which represents the primary mode of energy supply during daytime.

The results demonstrate that system efficiency increases progressively with load resistance, reaching a peak value of approximately 96.6% at an optimal resistance of 41 Ω. This maximum efficiency indicates effective impedance matching between the source and load, as well as optimal operation of the push–pull inverter and LCL filtering stages. At lower resistance values, the efficiency is comparatively reduced due to higher current flow, leading to increased conduction losses within the switching devices and associated components.

Beyond the optimal operating point, a gradual decline in efficiency is observed as the load resistance increases further. This behavior can be attributed to reduced power transfer efficiency and increased mismatch between system components. Despite this decline, the system maintains relatively high efficiency across a broad range of operating conditions, highlighting its robustness and adaptability.

Overall, the efficiency characteristics confirm that the proposed system performs optimally within a defined load range while maintaining stable and reliable operation beyond this region. The high peak efficiency and consistent performance validate the effectiveness of the battery-less configuration, reinforcing its suitability for energy-efficient and sustainable power supply in remote island applications.

CONCLUSION

This study presents the design and simulation of a battery-less hybrid renewable energy system integrating solar photovoltaic (PV) and fuel cell technologies to ensure continuous and reliable power supply for remote island regions. The proposed system effectively combines solar energy for daytime operation and fuel cell technology for non-daylight conditions, thereby achieving uninterrupted 24-hour power generation without the need for battery storage.The simulation results demonstrate that the system achieves stable voltage and current outputs with improved power quality through the use of a transformer-coupled push–pull inverter and LCL filtering stages. The incorporation of a matrix converter further enables efficient conversion to balanced three-phase output, expanding the system's applicability to a wider range of loads. The system attains a maximum efficiency of approximately 96.6% under optimal load conditions, indicating high performance and minimal energy losses. The elimination of battery storage significantly reduces system cost, maintenance complexity, and environmental impact, making the proposed configuration a practical and sustainable solution for off-grid electrification. Overall, the findings confirm that the proposed hybrid system is technically feasible, economically viable, and suitable for reliable power delivery in island and remote areas. Future work will focus on improving system performance through advanced control strategies, proper grid synchronization, and real-time energy management. Additionally, the development of an experimental prototype and field implementation will be essential to validate the system under real operating conditions and further enhance its practical applicability.

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