An Efficient Approach for Synchronous Generator-Based Diesel-PV Hybrid Micro-Grid with Power Quality Controller

T. Hussain[A], Anand Singh[B], Manish Khemariya[C]

***Abstract*—Incorporating renewable energy sources, such as photovoltaic (PV) systems, into microgrids offers a promising path for sustainable and robust power generation. However, the intermittent nature of renewable energy sources requires robust solutions to ensure continuous power supply and high-quality electricity. This abstract presents an innovative and effective method for a hybrid microgrid combining a synchronous generator, diesel, and PV sources, enhanced by a sophisticated power quality controller. The proposed hybrid micro-grid system is designed to address the challenges associated with intermittent and variability of PV generation, ensuring uninterrupted power supply to meet the demands of both urban and remote areas. This approach leverages the synchronous generator's reliable power output, complemented by the clean and renewable energy generated by PV systems. Through advanced control algorithms and innovative technology, this system optimally manages the power flow. A power quality controller is incorporated into the hybrid microgrid, which improves the stability and reliability of the electricity supply. This controller actively monitors and regulates voltage and frequency levels, mitigating fluctuations and disturbances caused by sudden load changes or intermittent renewable energy generation. The combination of a synchronous generator, PV systems, and a power quality controller not only enhances the energy efficiency of the microgrid but also contributes to reducing environmental impact. The objective of this research is to offer a sustainable and cost-effective solution for meeting energy demands while upholding high power quality standards.**

***Keywords*—Hybrid Micro-Grid; Synchronous Generator; Power Quality Controller; Diesel-PV Integration; Renewable Energy.**[1]

I. INTRODUCTION

Conventional fossil fuel-based power plants have been significant sources of air and water pollution. Given the global depletion of fossil fuel reserves and mounting concerns surrounding the environmental ramifications of conventional energy production, there is an increasing interest in the adoption of distributed generation (DG) technologies that utilize renewable energy sources like solar, wind, and biomass [1]. This approach is increasingly regarded as a promising strategy to address the rising demand for energy while simultaneously mitigating environmental concerns. To enable the smooth integration of renewable energy sources into existing power grids without interruption, there is a continuous development of new technologies.

DG units are swiftly gaining adoption within modern power grids, and concerted efforts are being made to ensure the harmonious integration of these renewable sources [2]. Nevertheless, because of the intermittent nature of renewable energy supply, often dictated by weather conditions, the direct integration into utility power grids has the potential to compromise system stability and reliability. To surmount this challenge, the concept of microgrids has come to the face [3]. Microgrids are localized distribution systems that incorporate distributed generation, energy storage, decentralized loads, and a variety of supporting technologies encompassing sensing, control, communication, protection, and supervision [4]. They can operate in conjunction with or independently from the primary power grid. The introduction of microgrids enables an augmented penetration of low-capacity DG units, predominantly situated at customer sites. This alleviates load congestion within the conventional utility grid and bolsters overall power generation capacity by leveraging the microgrid to supply a portion of the loads. Microgrids also afford enhanced control flexibility to meet stringent power quality standards and enhance system reliability [5]. Recent progress in power electronic devices and control technologies has simplified the integration of renewable-based DG units into microgrids. However, power quality issues can surface within microgrids due to factors like the irregular nature of renewable energy sources and disturbances originating in the primary power grid, such as voltage sags. High-speed switching in inverters can precipitate harmonic distortions at the interface, and the presence of nonlinear, unbalanced, and reactive local loads can further deteriorate power quality [6]. In scenarios where power quality is compromised by disturbances from the grid, a microgrid can transition to an isolated mode, functioning autonomously and independently of the main power grid. This serves as a contingency solution to maintain a consistent power supply and uphold satisfactory power quality standards within the microgrid [7].

The Diesel-PV Hybrid Micro-Grid is an advanced and integrated energy system that leverages the strengths of both conventional and renewable energy sources, providing a

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versatile and resilient solution for various energy scenarios [8]. At the heart of the Diesel-PV Hybrid Micro-Grid lies the synthesis of two fundamentally distinct energy sources - diesel generators and photovoltaic (PV) systems [9]. Diesel generators have long been prized for their reliability and ability to deliver a consistent power supply. They are particularly well-suited for scenarios where grid connection reliability is questionable or in remote locations where alternative power sources are scarce. However, their reliance on fossil fuels has raised environmental concerns, making their long-term sustainability questionable. In contrast, PV systems harness the abundant and renewable energy of the sun, offering a clean and green source of electricity. Nevertheless, the intermittent and variable nature of solar energy introduces challenges related to maintaining a stable power supply [10]. The Diesel-PV Hybrid Micro-Grid, with its integration of these energy sources, capitalizes on the complementary strengths of each. During daylight hours, the PV systems harvest solar energy, and the surplus power generated can be stored or directed into immediate use. When solar energy production wanes, diesel generators seamlessly assume the role of primary power generation. This hybridization not only guarantees continuous power availability but also reduces the carbon footprint, making it an attractive solution for locations seeking to balance reliability with environmental responsibility [11].

The hybrid plant can integrate energy storage devices, including supercapacitors and/or batteries, leading to a significant decrease in the fuel consumption of a diesel generator. The addition of a battery energy storage system (BESS) is particularly valuable when used alongside a DG in a standalone microgrid, enhancing the reliability of the hybrid system [12].

Different optimization methods have been employed in hybrid energy systems with storage to tackle various scenarios. For example, in [13], a particle swarm optimization technique was used to identify the optimal configuration for the generation and storage systems. In this case, the objective function considered the cost of energy and sought to determine the appropriate quantities of batteries, PV panels, wind turbines, and DG units. Another study, documented in [14], employed the social spider technique to optimize the system based on minimizing operational costs, while [15] employed an analytical approach for the same purpose. Researchers investigated the reduction of operating costs by taking into account factors such as battery state of charge and fluctuations in load demand [16].In the Indian context, numerous studies have been carried out to determine the ideal configuration of hybrid systems incorporating PV, wind, DG, and batteries, using tools such as HOMER [17]. In a residential case study, researchers investigated nine scenarios that incorporated a hybrid converter system with PV, wind, DG, and BSS with the aim of minimizing both the total net present cost and greenhouse gas (GHG) emissions [18]. In [19], researchers utilized a MBC for the PV system to optimize power extraction. They also employed a line-commutated inverter (LCI) to manage the charge and discharge cycles of the battery.

In [20] the researchers examined the field of power quality control within a diesel-PV hybrid micro-grid featuring synchronous generators. The study focused on the implementation of AI techniques to improve power quality. More specifically, the authors suggested the utilization of a smart control system based on neural networks and fuzzy logic. The main objective of this intelligent control system was to reduce power interruptions, lower harmonic distortion, and minimize voltage fluctuations. To assess the efficiency of the proposed controller, the researchers conducted a series of extensive modeling and experiments. In [21], they introduce a comprehensive framework for the design and control of a diesel-PV hybrid microgrid incorporating a synchronous generator. The study takes a multifaceted approach, evaluating key aspects of the system, including power quality, economic feasibility, and dynamic performance. Of particular focus is the analysis of different control algorithms and their impact on the system's stability, as well as the allocation of power between renewable and conventional energy sources. This research endeavors to provide a holistic understanding of the intricacies involved in optimizing the operation of such hybrid microgrids.

In [22] control techniques utilized within synchronous generator-based diesel-PV hybrid micro-grids. The authors underscore the critical importance of upholding stability and power quality in these systems. They conducted a comprehensive analysis of various control algorithms, including approaches such as fuzzy logic control, neural networks, and model predictive control. The study places particular emphasis on elucidating the strengths and weaknesses inherent in each control technique. Additionally, it provides valuable insights into the practical implementation of these control strategies and their performance in the context of hybrid microgrid systems. This research offers a valuable contribution to the optimization of control mechanisms within such intricate and dynamic energy systems. In [23] investigated the practical application of a power quality controller aimed at enhancing the stability of voltage and frequency within a diesel-PV hybrid microgrid relying on synchronous generators. Research focuses on the development of a comprehensive control strategy with the primary objective of mitigating power fluctuations and harmonic distortions. This strategy is meticulously designed to ensure a consistent and high-quality power supply to the various connected loads within the microgrid. The intermittent and variable nature of solar power presents challenges in maintaining a continuous and stable electricity supply. To bridge this gap, our research focuses on a hybrid micro-grid that combines the steady power generation of a synchronous generator with the clean and renewable energy output from PV systems. By effectively blending these energy sources, this approach strives to provide uninterrupted power for both urban and remote regions, demonstrating the versatility of micro-grid technology.

A key component of this innovative approach is the incorporation of a power quality controller within the micro-grid system. This controller plays a pivotal role in enhancing the stability and reliability of the electricity supply. It actively monitors and regulates voltage and frequency levels, thereby mitigating fluctuations and disturbances that can occur due to sudden load changes or intermittent renewable energy generation. By ensuring consistent power quality, this hybrid micro-grid contributes to improved operational efficiency, making it a crucial development in the quest for a sustainable and resilient energy future. This abstract offers an overview of this multifaceted research, which combines the reliability of synchronous generators, the environmental benefits of PV systems, and the power quality enhancements brought about by advanced control technology in a concerted effort to revolutionize micro-grid design and operation.

The motivation for this work arises from the urgent necessity to tackle the challenges linked to the integration of intermittent renewable energy sources, such as PV systems, into microgrids. While renewables offer sustainable energy solutions, their variability poses reliability issues. The motivation for this research is to develop a comprehensive and efficient hybrid microgrid system that combines the reliability of synchronous generators with the environmental benefits of PV systems while ensuring uninterrupted power supply through a power quality controller. This holistic approach strives to meet the evolving energy demands of both urban and remote areas while upholding high power quality standards and minimizing environmental impact. The paper is structured as follows: Section 2 outlines the research methodology, Section 3 elaborates on the MPPT control of the PV system, Section 4 discusses the control strategy, and Section 5 presents the results.

II. RESEARCH METHODOLOGY

The proposed hybrid micro-grid system comprises a synchronous generator, a PV array, energy storage, and a power quality controller. The synchronous generator serves as the primary power source, with the PV array providing additional power during periods of high solar irradiance. The energy storage system, which includes batteries, is integrated to store surplus energy and guarantee a continuous power supply during periods of reduced solar irradiance.

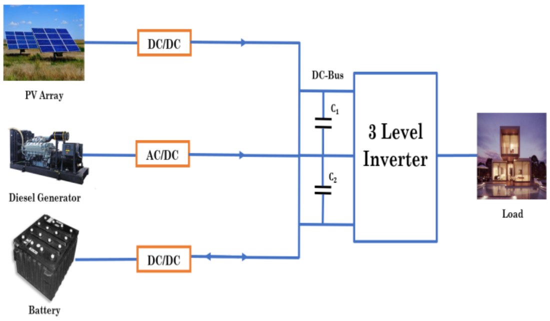

Fig. 1.Proposed Hybrid System Model

Fig. 1 showcases an innovative hybrid system that integrates lithium batteries, photovoltaic (PV) panels and a diesel generator at different speeds. This system offers a comprehensive power solution by combining renewable energy sources with a backup generator. The DC bus link plays a crucial role in connecting the PV panels and batteries to the power source. This connection is facilitated by employing three-level DC-DC converters, ensuring efficient power transfer and management.

In this study, offered a micro-grid architecture that is both insulated and uses numerous energy sources, including a diesel generator, a BSS, and a renewable energy system based on photovoltaic (PV) panels. Variable-speed diesel generators are used to overcome the drawbacks of fixed-speed diesel generators, such as wasteful fuel consumption, excessive pollutant emissions even during low energy demand, and continuous noise production regardless of power requirements.

The energy management system put forward in this proposal incorporates the utilization of three-level power converters. These devices provide numerous advantages in comparison to traditional two-level converters. A significant benefit is their capacity to deliver greater accuracy in voltage adjustment. This characteristic enhances the control and regulation of power flow within the system.

Moreover, the implementation of three-level power converters brings about a noteworthy reduction in harmonic distortion in the load current. This reduction in harmonics ensures a cleaner and more stable power supply to the connected devices. By reducing the presence of harmonics, the system improves the overall quality of the electrical energy supplied to the microgrid.

III. MPPT CONTROL OF THE PV SYSTEM

MPPT control is a technique employed in PV systems to optimize the power output of solar panels by tracking the MPP of the PV array. The control algorithm fine-tunes the operating point of the PV system, ensuring it operates at the MPP regardless of variations in environmental conditions, such as temperature, shading, and fluctuations in solar irradiance.

A commonly employed MPPT control algorithm is the Perturb and Observe (P&O) algorithm. It computes the power at various operating points and modulates the duty cycle of a DC-DC converter to follow the MPP. The fundamental equation for the P&O MPPT control algorithm is as follows:

Step 1: Measure the PV array voltage (V) and current (I).

Step 2: Calculate the instantaneous power (P) as the product of voltage and current: $P = V * I$.

Step 3: Perturb the duty cycle (D) of the DC-DC converter.

Step 4: Measure the new PV array voltage (V') and current (I').

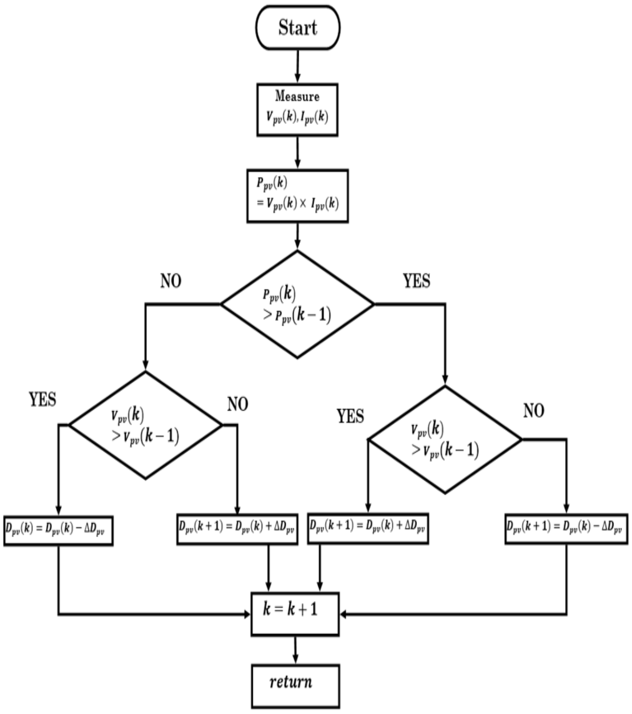

Fig. 2 Flow chart for P and O MPPT

Step 5: Calculate the new instantaneous power (P') as the product of the new voltage and current: $P' = V' * I'$.

Step 6: Compare the new power (P') with the previous power (P).

If P' is greater than P, the converter is moving in the right direction. Continue perturbing in the same direction.

If P' is less than P, the converter has moved past the MPP. Change the perturbation direction.

Step 7: Repeat steps 3 to 6 until the MPP is reached or a convergence criterion is met.

The P&O algorithm continuously adjusts the duty cycle based on the power comparison to search for the MPP. It is a simple and widely used MPPT control algorithm, although it may suffer from oscillations around the MPP under certain conditions. Various modifications and advanced MPPT algorithms are available to address these issues and provide more efficient and reliable MPPT control in PV systems.

IV. CONTROL STRATEGY

Distributing the load demand power across various renewable energy sources, photovoltaic (PV) systems, is at the heart of the suggested control technique. Because of the coupling point between the renewable energy sources and the load, this hybrid electromagnetic system experiences interactions between disturbances. The control strategy considers the frequency components of the fluctuations to address these dynamic interactions. Any disturbances in the system will be amplified and transmitted to the current values if the DC bus voltage is held constant. Low-pass filters (LPF) are used to establish the power references for the DG units and the batteries.

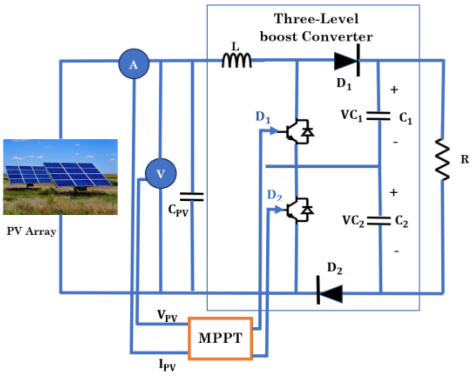

Fig. 3. PV panel feeding three level Boost convertor with MPPT

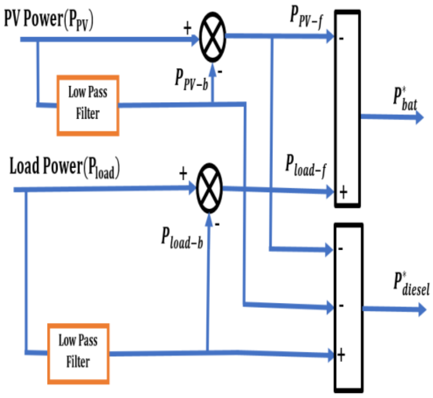

Fig. 4 Battery and Diesel Generator Power Extraction

The power control sub-system plays a vital role in regulating the flow of electrical current between the DC bus and the battery pack. It consists of a buck/boost converter, which is responsible for regulating the current to maintain optimal conditions for charging or discharging the batteries.

In this specific study, lithium-ion batteries have been selected for their exceptional energy density and efficiency. They outperform other battery types such as NiMH, NiCd, or lead-acid in terms of their ability to store and release energy effectively.

The battery's output voltage, referred to as V_{Bat}, is not a simple linear relationship. It is influenced by two main factors: the battery's SoC and the nonlinearity of the current. SoC refers to the amount of charge remaining in the battery, and it affects the battery's performance and voltage output. Battery's output voltage V_{Bat} is given as in equation (1).

$$V_{Bat} = V_{OP} - R_{Bat} * i_{Bat} - K_b \frac{Q}{Q - i_t} i_t + A_b e^{-B.i} t - K_b \frac{Q}{Q - i_t} i_t \quad (1)$$

$$Pol_{res} = K_b \frac{Q}{i_t - 0.1Q} \quad (2)$$

The current flowing into or out of the battery can also introduce nonlinear effects due to various factors like internal resistance and chemical processes. Battery current I_{Bat} is defined in equation (3). Voltage gains of bidirectional converter of battery during charging $\alpha_{Boost-Bat}$ and discharging $\alpha_{Buck-Bat}$ are given in equations (4) and (5).

$$I_{Bat} = \frac{V_{Bus}}{V_{Bat}} I_{BatBus} \quad (3)$$

$$\alpha_{Buck-Bat} = \frac{V_{Bat} + V_{control-loop-output}}{V_{Bus}} \quad (4)$$

$$\alpha_{Boost-Bat} = 1 - \frac{V_{Bat} - V_{control-loop-output}}{V_{Bus}} \quad (5)$$

V. RESULT & DISCUSSION

Simulations are conducted using Matlab/Simulink to demonstrate an energy management approach for a micro-grid system. The micro-grid system features an 800 V DC bus that connects various power sources, including 22 kW of PV arrays, 65 kW of backup batteries, and 25 kW of diesel generation.

The DC bus was connected to the adaptable load through a three-stage inverter. To accommodate the 372 V peak voltage of the battery pack, a bidirectional buck-boost converter is employed to regulate energy management. During the simulation, a value of 460 V was selected to control the load reference voltage on the q-axis, while a reference value of 400 V was used for the load reference voltage on the d-axis. Finally, to maintain stability and balance, a reference voltage of 0 V was employed for the q-axis. These carefully selected reference voltages played a crucial role in our study, enabling us to analyze and manipulate the electrical parameters effectively.

By employing different energy resources and their associated controllers, efficient management of energy from DG (distributed generation) sources in the micro-grid is achieved. Multiple scenarios are simulated, with a particular focus on those involving PV solar energy and load shifting. Fig. 4 illustrates how the DC-bus connection distributes power generated by the solar panels within the microgrid. The distribution of power is influenced by the amount of irradiation the solar panels receive daily. On days without clouds, the graph shown in Fig. 5 exhibits a fluctuation of 3 to 15 hours due to the presence of clouds.

The variations observed in the power allocation curve can be attributed to the movements of the clouds. The presence of clouds induces fluctuations in the incident solar radiation on photovoltaic panels, thereby resulting in alterations in the electrical output. Between the hours of 8 AM and 12 PM, the curve attains its peak values. Nonetheless, within this timeframe, there are intermittent occurrences where cloud cover results in a momentary decline of 50% in power output lasting a few minutes.

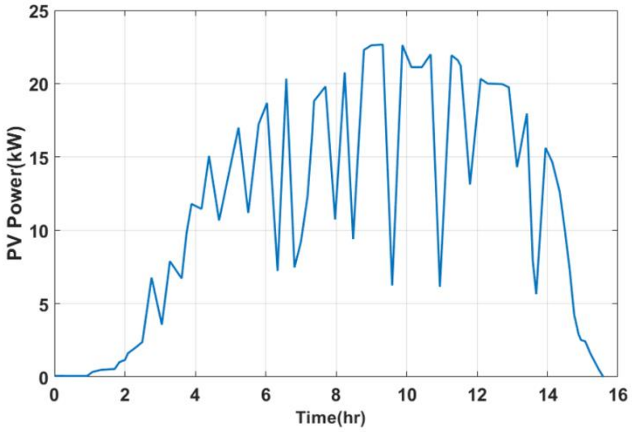

Fig. 5 PV Power

Fig. 6 shows how the integration of PV panels with load demand has affected the development of distributed generation (DG) energy. Consolidating low-frequency components that stand for the site's dynamic power needs yields the DG power profile. This evolution signifies the dynamic relationship between the DG system, comprising PV panels, and the electrical load demand. PV panels, through their ability to convert sunlight into electricity, contribute to the overall DG power generation. The load demand, which represents the amount of electrical power required at the site, fluctuates over time due to various factors such as changing usage patterns and external influences.

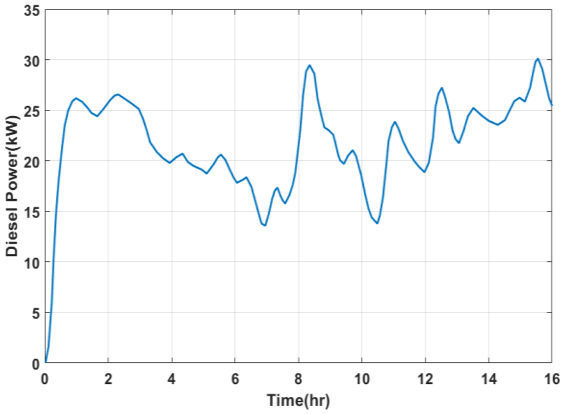

Fig. 6 Power Output of Diesel Generators at the Coupling Point

Renewable energy resources generate more power than the load demands. This excess energy is stored in the batteries to be used later when the renewable energy generation is insufficient to meet the load requirements. Fig. 7 illustrates the variation in load power demand over a period of time. The graph shows that the minimum power demand of 22 kW occurs at around 7 a.m., while the maximum power demand of 44 kW happens at approximately 3 p.m. This suggests that the load's power requirements fluctuate throughout the day. Batteries play a critical role in ensuring a stable and dependable power supply to the load. They serve as an energy buffer, absorbing and storing the excess energy generated by the renewable energy resources during periods of high production. This excess energy would otherwise go unused and be wasted.

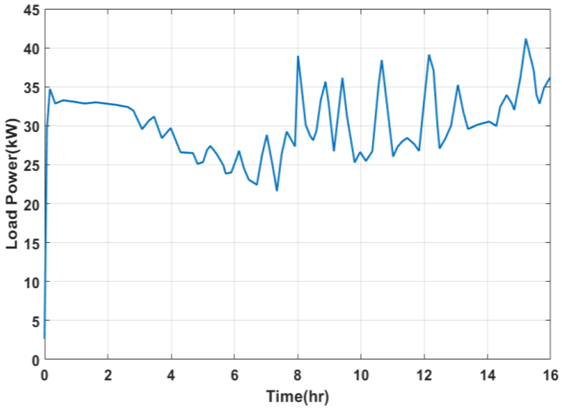

Fig. 7 Power demand of the load

CONCLUSION

The integration of renewable energy sources, particularly PV systems, is instrumental in achieving sustainability and resilience in power generation. Solar energy, harnessed through PV systems, offers a clean and abundant source of power that can be especially beneficial in microgrid applications. However, the intermittent nature of solar energy generation has been a persistent challenge in ensuring a consistent and high-quality electricity supply, especially in remote or off-grid locations. The core strength of the approach presented in this work lies in its harmonious fusion of the reliability of synchronous generators with the clean and renewable energy generated by PV systems. By combining these complementary sources of power, and by applying advanced control algorithms and innovative technology, the hybrid microgrid optimizes power flow. This optimization guarantees a continuous and high-quality electricity supply, regardless of the intermittent nature of solar energy. Power quality is crucial in microgrids because it directly impacts the stability and reliability of the electricity supply. Inconsistent power quality, characterized by voltage and frequency fluctuations, can lead to equipment damage, operational disruptions, and inefficiencies in sensitive loads. The inclusion of a power quality controller further solidifies the reliability and stability of the electricity supply. This controller actively monitors and regulates voltage and frequency levels, effectively mitigating fluctuations and disturbances caused by varying load requirements and the intermittent nature of renewable energy generation. This means that consumers in both urban and remote areas can benefit from a consistent and stable power supply, which is critical for various applications, from everyday life to critical infrastructure. Beyond its technical prowess, this hybrid system makes a noteworthy contribution to environmental sustainability. By reducing the reliance on traditional diesel generators, it significantly cuts the carbon footprint associated with conventional power generation. This decrease in greenhouse gas emissions is in line with global endeavors to address climate change and shift towards a more sustainable energy ecosystem.

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