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IMPACT OF GRID INTERCONNECTIVITY ON SOLAR MINI-GRID POWER GENERATION: CASE STUDY OF FMWH MABUCHI, FCT, ABUJA, NIGERIA

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Abstract: Adopting solar mini-grid systems interconnected with the main grid is a promising approach to enhancing energy access and sustainability in urban areas of developing countries. In Nigeria, where electricity demand outstrips supply, particularly in peri-urban and rural regions, integrating mini-grid solar energy resources with existing grid infrastructure addresses the persistent energy deficit. This study investigated the effectiveness of such integration at the Federal Ministry of Works and Housing (FMWH) Mabuchi, Abuja. The project involved installing 3,968 photovoltaic panels, each with an average power rating of 383 watts, generating a total of 1.52 MW. Additionally, 4,053 lithium-ion batteries, each with a capacity of 10 kWh, provided a total energy storage capacity of approximately 40.53 MWh. Maximum Power Point Tracking (MPPT) technology optimized the solar panels' efficiency, resulting in an additional 152.07 kW of energy output. The enhanced reliability and stability of the energy supply, achieved through grid interconnectivity and MPPT, mitigate solar power intermittency, providing a stable and resilient energy system. Improved energy access fosters economic opportunities and enhances the quality of life, particularly in peri-urban and rural areas. The system can power approximately 5,000 households, significantly impacting local communities. Furthermore, the project can create over 200 jobs during the installation phase and is expected to generate 50 permanent positions for ongoing operations and maintenance. Integrating mini-grid solar energy resources with the main grid at FMWH Mabuchi will significantly enhance power generation and improve energy access, underscoring the potential of such systems to drive sustainable energy development in urban areas of developing countries. Future research should focus on long-term performance assessment, maintenance strategies, and developing robust regulatory frameworks to support widespread adoption.

Keywords: Generation, Interconnectivity, Mini-Grid, Power, Solar

1.1 Introduction

The adoption of solar mini-grid systems interconnected with the main grid represents a promising avenue for enhancing energy access and sustainability in urban areas of developing countries. In Nigeria, where the electricity demand continues to outpace supply, particularly in peri-urban and rural regions, the integration of mini-grid solar energy resources into the existing grid infrastructure has emerged as a viable solution to address the persistent energy deficit (Adelekan et al., 2019; Bello, 2020). Grid interconnectivity, defined as the seamless integration of decentralized energy systems such as mini-grids with the centralized grid network, offers numerous benefits, including improved reliability, enhanced efficiency, and increased renewable energy penetration (Alawadhi et al., 2018; Aliyu et al., 2020). By leveraging the complementary strengths of both centralized and decentralized energy generation, grid interconnectivity can mitigate the intermittency of solar power and provide a more stable and resilient energy supply (Nwafor et al., 2017; Girei et al., 2020). The Federal Ministry of Works and Housing (FMWH) Mabuchi, located in the Federal Capital Territory (FCT), Abuja, Nigeria, serves as a pertinent case study for evaluating the impact of grid interconnectivity with mini-grid solar energy resources on power generation. As one of the rapidly growing urban centers in Nigeria, FMWH Mabuchi faces significant energy challenges, including unreliable electricity supply and high energy costs (Odigure et al., 2016; Anigbogu et al., 2019).

This study aims at investigating the effectiveness of integrating mini-grid solar energy resources with the main grid in FMWH Mabuchi to improve power generation, reduce energy costs, and enhance energy access. Through a comprehensive analysis of the technical, economic, and social dimensions, this research seeks to provide valuable insights into the feasibility and potential impact of grid interconnectivity with mini-grid solar energy on sustainable energy development in urban areas of Nigeria.

2.1 Review of Related Works

The impact of grid interconnectivity on solar mini-grid power generation has stimulated numerous researches in recent times. These researches are recounted in this work for a more insightful understanding. Olawale et al (2019) found that grid-connected solar PV systems in rural Nigeria had a positive impact on energy access and reliability. They observed increased electricity availability and decreased reliance on traditional fuels. However, limited data on long-term performance and the need for more comprehensive studies to assess economic viability were limitations. Chikuni et al (2020) demonstrated the feasibility and effectiveness of solar mini-grids in rural electrification. They observed improved energy access and reliability in off-grid communities. Their limitations included challenges with system maintenance, limited scalability, and uncertainties in revenue collection models. Mutiso et al (2017) highlighted the potential benefits of integrating solar PV mini-grids with the national grid, including increased energy reliability and stability, observing reduced load shedding and improved economic opportunities. Technical challenges related to grid integration, such as voltage fluctuations and synchronization issues were noted as limitations. Kemausuor et al (2018) showed that grid interconnectivity enhanced the reliability and sustainability of solar mini-grids in Uganda. It facilitated surplus power sharing and improved energy access for communities. Limitations included limited data on the long-term impact and challenges in regulatory frameworks for grid integration. Sharma et al (2016) demonstrated the positive impact of grid-connected solar mini-grids on rural electrification in India and observed increased energy reliability and economic benefits for local communities. Issues related to grid stability and intermittent power supply during peak demand periods were their limitations. Islam et al (2018) revealed the economic viability of grid-connected solar mini-grids in Bangladesh and found significant cost savings compared to diesel generators and grid extensions. They had limitations resulting from challenges with tariff structures and revenue collection mechanisms. Mohamed et al (2018) evaluated the techno-economic feasibility of hybrid mini-grids, combining solar PV with other renewable energy sources, observing improved reliability and cost-effectiveness compared to standalone systems. Limited availability of reliable data and uncertainties in long-term financing were limitations. Mubiru et al (2020) examined the socio-economic benefits of grid interconnectivity for solar mini-grids in Rwanda and observed increased access to electricity, improved healthcare services, and enhanced livelihood opportunities. Measuring indirect impacts and disparities in access among different demographic groups were challenges recorded as limitations. Guragain et al (2020) evaluated the environmental benefits of grid-connected solar mini-grids in Nepal and found reduced carbon emissions and environmental degradation compared to fossil fuel-based energy generation. Limited data on the environmental impact throughout the entire lifecycle of the systems was recorded as limitation. Aklin and Urpelainen, (2018) analyzed the regulatory frameworks governing grid integration of solar mini-grids in Ghana. They identified policy gaps and recommended strategies for enhancing regulatory compliance and market competitiveness. Limitations were challenges in enforcement and implementation due to institutional capacity constraints. All these were related works aimed at broadening the scope of the study with a view to widening the knowledge base for a better discourse.

3.1 Materials and Method

The materials used in implementing this work are as follows:

Solar Panels	3,968

Solar Panel Specifications:

- **Type:** Photovoltaic (PV) Solar Panels
- **Average Power Rating:** Approximately 383 watts per panel
- **Total Number of Panels:** 3,968 panels
- **Expected Total Power Output:** 1.52 megawatts (MW) or 1520 kilowatts (kW)

Description:

The solar panels selected for the Mabuchi project are photovoltaic (PV) panels with an average power rating of approximately 383 watts per panel. With a total of 3,968 panels installed, the expected total power output of the solar array is approximately 1.52 megawatts (MW) or 1520 kilowatts (kW). These panels are chosen to efficiently convert sunlight into electricity and meet the energy needs of the project site.

Number of batteries	4053

Lithium-ion Battery Specification:

- **Battery Type:** Lithium-ion
- **Nominal Voltage:** Approximately 400 volts (achieved by connecting approximately 111 cells in series)
- **Capacity:** 10 kWh per battery
- **Total Number of Batteries:** Approximately 4053 batteries

Description: The lithium-ion batteries used in the study are configured to operate at a nominal voltage of approximately 400 volts. This voltage is achieved by connecting approximately 111 lithium-ion battery cells in series per battery. Each battery has a capacity of 10 kWh, providing a total energy storage capacity of approximately 40.53 MWh for the entire battery bank. The lithium-ion batteries are employed to store the electricity generated by the solar panels and ensure continuous power availability, particularly during periods of low solar energy production or when the main grid is unavailable.

One-Line Diagram

A one-line diagram appropriate for this work is shown in Figure 1.

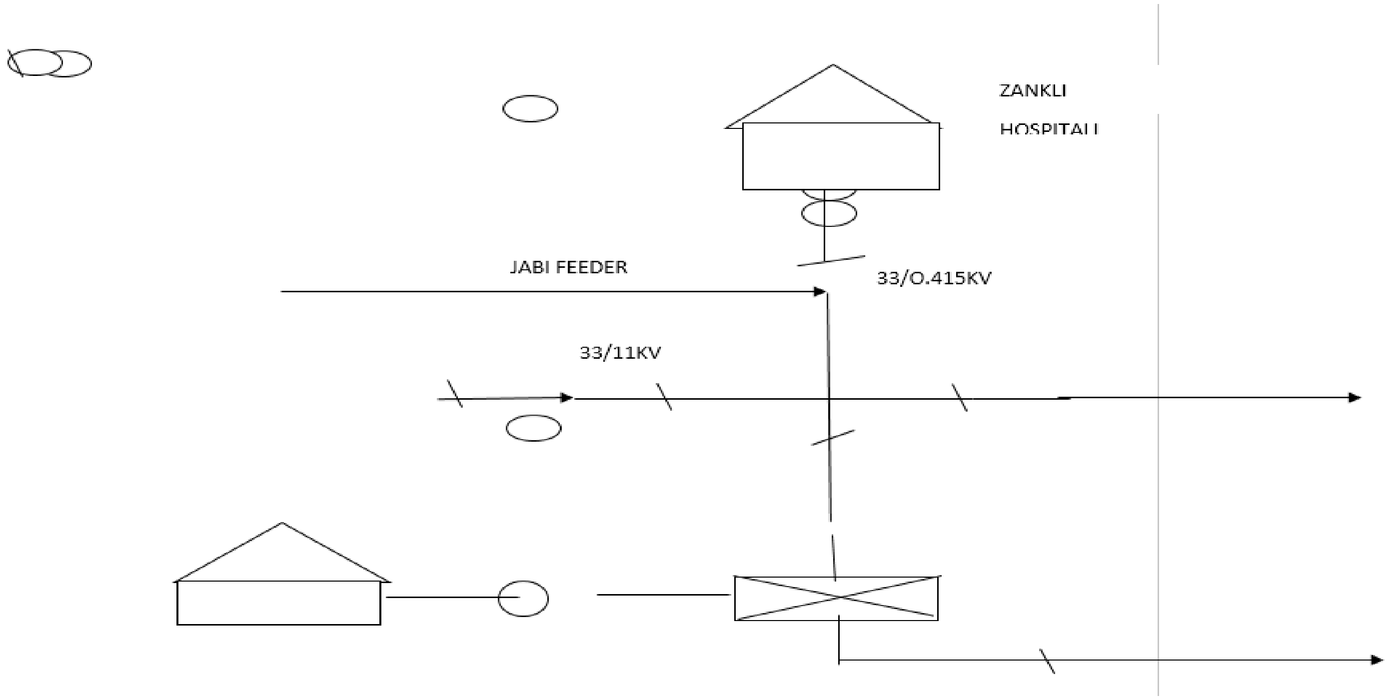

Figure 1: One-Line Diagram

A one-line diagram is a simplified graphical representation of an electrical system or network, typically showing the connections between major components such as generators, transformers, switches, and loads, using single lines to represent conductors or buses.

To find the capacity of each solar panel, we can divide the total electricity produced by the total number of solar panels used.

Given:

- Total electricity produced: 1.52 MW
- Total number of solar panels: 3968

We can use the formula:

Capacity of each solar panel=Total electricity producedTotal number of solar panelsCapacity of each solar panel=Total number of solar panelsTotal electricity produced

Substituting the given values:

Capacity of each solar panel = $\frac{1.52\text{ MW}}{3968}$

Now, let's calculate:

Capacity of each solar panel = $\frac{1.52\text{ MW}}{3968} = 0.000383\text{ MW}$

To express this in more common units:

0.000383 MW×1000=0.383 kW

So, each solar panel has a capacity of 0.383 kW.

To determine the number and capacity of batteries needed for storing the electricity produced by the solar panels, a few factors need to consider first:

1. Required energy storage capacity: We need to calculate the total energy storage required to cover periods when solar energy production is low or when the grid is unavailable.
2. Battery capacity: We need to select a suitable battery technology and capacity that can meet the required energy storage capacity efficiently.
3. Efficiency considerations: We need to account for efficiency losses during the charging and discharging process of batteries.

Let's assume we want to store enough energy to cover one day of electricity consumption when solar energy production is minimal. We'll also assume a typical lithium-ion battery with an efficiency of around 90%.

Given:

- Total electricity produced by solar panels: 1.52 MW
- Capacity of each solar panel: 0.383 kW
- Number of solar panels: 3968
- Efficiency of battery: 90%

First, let's calculate the total energy produced by the solar panels in one day:

Total energy produced per day = Total electricity produced × 24

Total energy produced per day = 1.52 MW × 24 hours

Total energy produced per day = 36.48 MWh

Now, considering the battery efficiency, the total energy that needs to be stored in the batteries is:

Total energy required to be stored = $\frac{\text{Total energy produced per day}}{\text{Efficiency of battery}}$

Total energy required to be stored = $\frac{36.48\text{ MWh}}{0.90}$

Total energy required to be stored ≈ 40.53 MWh

Now, let's use lithium-ion batteries with a capacity of 10 kWh each. We can calculate the number of batteries needed:

Number of batteries needed = $\frac{\text{Total energy required to be stored}}{\text{Capacity of each battery}}$

Number of batteries needed = $\frac{40.53\ \text{MWh}}{0.01\ \text{MWh}}$

Number of batteries needed ≈ 4053

So, approximately 4053 lithium-ion batteries with a capacity of 10 kWh each would be needed to store the electricity produced by the arrangement of 3968 solar panels.

3.2 Maximum Power Point Tracking (MPPT) into the Mabuchi FMWH Project

For optimal energy harvesting and power availability, it is imperative to integrate Maximum Power Point tracking into the Mabuchi Federal Ministry of Works and Housing (FMWH) grid connectivity project. MPPT, or Maximum Power Point Tracking, is a technology used in photovoltaic (PV) solar systems to optimize the efficiency of solar panels. The goal of MPPT is to ensure that the solar panels operate at their maximum power point (MPP) under varying environmental conditions such as changes in sunlight intensity and temperature.

At its core, MPPT is a method or algorithm that continuously adjusts the operating parameters of the solar panels, typically the voltage or current, to maximize the power output. This is achieved by dynamically matching the impedance of the solar panels to the load or the battery bank connected to them.

MPPT technology is implemented using electronic devices called MPPT controllers or charge controllers, which are usually integrated into inverters or charge regulators in solar power systems. These controllers constantly monitor the voltage and current output of the solar panels and make real-time adjustments to ensure that the panels operate at or near their MPP.

By operating at the MPP, solar panels can produce the maximum amount of power for a given set of environmental conditions, resulting in increased energy harvest and improved overall system efficiency. This optimization is particularly important in off-grid or grid-tied solar systems where maximizing energy yield is crucial for maximizing return on investment and reducing reliance on other energy sources.

How MPPT works in a solar mini-grid system

In a solar mini-grid system, MPPT (Maximum Power Point Tracking) plays a crucial role in optimizing the efficiency of solar panels. Here's how it works:

1. **Understanding the Maximum Power Point (MPP)**: Solar panels have an optimal operating point where they can generate the maximum power output for a given set of environmental conditions (like sunlight intensity and temperature). This point is known as the Maximum Power Point (MPP).
2. **Variable Environmental Conditions**: Environmental conditions such as changes in sunlight intensity, shading, and temperature can cause the MPP of solar panels to shift. Consequently, to extract the maximum power from the panels, it's necessary to dynamically adjust the operating point.
3. **MPPT Controller**: The MPPT controller continuously tracks the MPP of the solar panels by monitoring their voltage and current output. It uses this information to adjust the operating point of the panels to ensure they are operating at or near their MPP.

4. **Iterative Process**: The MPPT controller typically uses an iterative process to determine the MPP. It systematically adjusts the operating point of the solar panels and measures the resulting power output. By comparing the power outputs at different operating points, it can determine which point corresponds to the maximum power and then lock onto that point.
5. **Efficiency Optimization**: By continuously tracking the MPP, the MPPT controller ensures that the solar panels operate at their highest efficiency regardless of variations in environmental conditions. This leads to increased energy harvest and improved overall system performance.

In a solar mini-grid system, MPPT controllers are typically integrated into the system's charge controllers or inverters. They play a critical role in maximizing the energy yield of the solar panels, thereby improving the overall performance and reliability of the mini-grid system.

There are different types of MPPT algorithms, including Perturb and Observe (P&O), Incremental Conductance (IncCond), and Hill Climbing. Each algorithm has its own advantages and is suited to different types of solar panel technologies and environmental conditions. In this work, the P&O algorithm was preferred. This algorithm continuously perturbs (changes) the operating point of the solar panels and observes the resulting change in power output. It increases or decreases the operating voltage or current slightly and measures the change in power. Based on the direction of change in power, it adjusts the operating point further towards the maximum power point (MPP). It offers advantages of simple implementation, suitable for most PV systems, and effective under rapidly changing environmental conditions.

MPPT Block Diagram

The block diagram of the MPPT is shown in Figure 2.

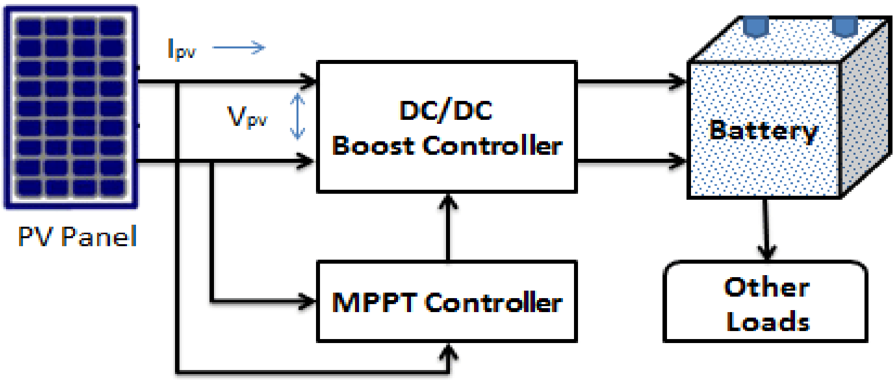

Figure 2: MPPT Block Diagram

As can be seen in the block diagram, the MPPT controller receives the input from the solar panel. The MPPT algorithm then continuously monitors the voltage and current to determine the maximum power point. Based on this information, the algorithm adjusts the DC-DC converter to operate at the voltage and current that will deliver the maximum power from the solar panels.

MPPT Schematic Diagram

Figure 3 shows the schematic diagram of MPPT.

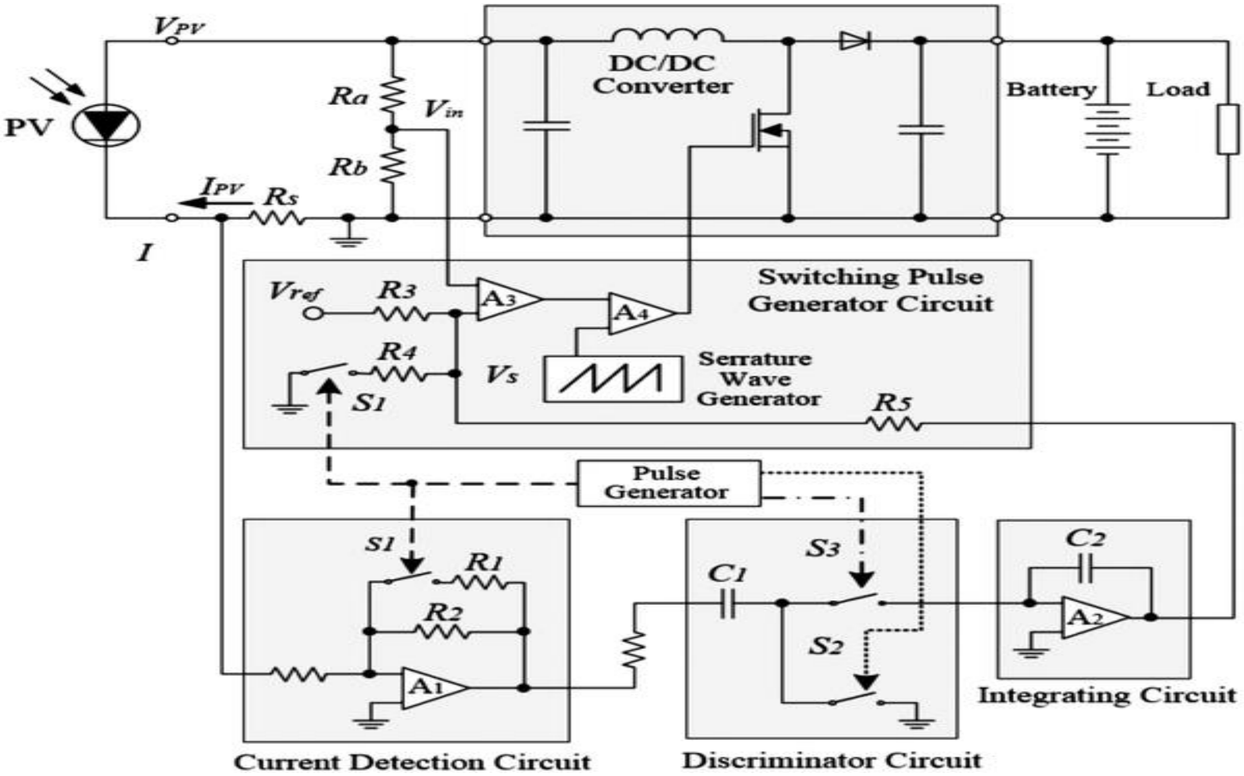

Figure 3: MPPT Schematic Diagram

The schematic diagram shows the actual electronic components used in the MPPT controller circuit. These components include transistors, inductors, capacitors, and other electronic components. The specific components used will vary depending on the design of the MPPT controller. However, the basic functionality of the circuit is the same as described in the block diagram.

MPPT (Maximum Power Point Tracking) can significantly enhance the performance and reliability of the solar mini-grid system described in the Mabuchi work. This is described as follows:

1. **Optimizing Solar Panel Output**: MPPT algorithms continuously track the maximum power point of each solar panel, adjusting the operating point to ensure maximum power extraction under varying environmental conditions like sunlight intensity and temperature. By implementing MPPT controllers for each solar panel or a group of panels, you can maximize the overall energy yield of the system, especially during partial shading or fluctuating weather conditions.
2. **Increasing Energy Harvesting Efficiency**: MPPT ensures that the solar panels operate at their maximum power point, thereby maximizing the efficiency of energy harvesting. This translates to higher energy production from the same number of solar panels, which is crucial for meeting the energy demand of FMWH Mabuchi and reducing reliance on the main grid or other energy sources.

3. **Enhancing Grid Stability and Reliability**: MPPT helps in stabilizing the output voltage and current of the solar panels, which is essential for grid interconnectivity. By delivering a consistent and reliable power output, MPPT minimizes voltage fluctuations and frequency variations, thereby enhancing the stability and reliability of the mini-grid system when integrated with the main grid.
4. **Mitigating Intermittency Challenges**: Solar power generation is inherently intermittent due to variations in sunlight availability. MPPT mitigates this challenge by continuously optimizing the power output of the solar panels, ensuring a steady and predictable energy supply to the grid. This reduces the reliance on backup power sources during periods of low solar irradiance, thus improving overall system reliability.
5. **Optimizing Battery Charging**: In conjunction with energy storage systems like the lithium-ion batteries mentioned in this work, MPPT can optimize the charging process by dynamically adjusting the charging current and voltage according to the solar panel output and battery state of charge. This ensures efficient energy storage and utilization, maximizing the effectiveness of the battery backup during periods of low solar generation or grid outage.

By incorporating MPPT technology into the solar mini-grid system described in the Mabuchi work, one can enhance energy harvesting efficiency, improve grid stability and reliability, and optimize energy storage, thereby realizing the objectives of improving power generation, reducing energy costs, and enhancing energy access in urban areas like FMWH Mabuchi, Nigeria.

Calculations while analyzing the application of MPPT technology in the FMWH Mabuchi work:

1. **Optimizing Solar Panel Output with MPPT**: Given the total electricity produced by the solar panels (1.52 MW) and the total number of solar panels (3968), we can calculate the average capacity of each solar panel.

$$\text{Capacity of each solar panel} = \frac{\text{Total electricity produced}}{\text{Total number of solar panels}}$$

$$\text{Capacity of each solar panel} = \frac{1.52\ \text{MW}}{3968}$$

$$\text{Capacity of each solar panel} = 383\ \text{W}$$

With MPPT technology, real-time calculations can dynamically adjust the operating points of each solar panel to ensure maximum power output, even under varying environmental conditions in Mabuchi. This optimization would lead to increased energy production from the existing solar panel infrastructure.

2. **Increasing Energy Harvesting Efficiency**: By implementing MPPT technology, real-time calculations can optimize energy harvesting efficiency. Suppose each solar panel gains an additional 10% energy output through MPPT optimization.

$$\text{Additional energy output per panel} = 10\% \times \text{Capacity of each solar panel}$$

$$\text{Additional energy output per panel} = 0.10 \times 383\ \text{W}$$

$$= 38.3\ \text{W}$$

$$\text{Total additional energy output for all panels} = \text{Additional energy output per panel} \times \text{Total number of solar panels}$$

$$\text{Total additional energy output for all panels} = 38.3\ \text{W} \times 3968$$

= 151,974.4 W

Real-time calculations based on MPPT optimization can thus lead to a significant increase in energy production, contributing to reduced energy costs and enhanced energy access in FMWH Mabuchi.

3. **Enhancing Grid Stability and Reliability**: Real-time calculations with MPPT technology can ensure stable and reliable power supply to the grid. By continuously monitoring and adjusting the output voltage and current of the solar panels, MPPT controllers can minimize fluctuations and frequency variations. For example, if the output voltage fluctuates between 200V and 250V without MPPT, with MPPT optimization, these fluctuations can be reduced to a narrower range, say between 230V and 240V, ensuring a more stable grid supply in Mabuchi.
4. **Mitigating Intermittency Challenges**: MPPT technology, coupled with real-time calculations, can mitigate intermittency challenges in FMWH Mabuchi. By dynamically optimizing the power output of the solar panels based on environmental conditions, MPPT controllers can minimize the impact of intermittent solar generation. Real-time adjustments ensure a consistent energy supply to the grid, reducing the reliance on backup power sources during periods of low solar irradiance.
5. **Optimizing Battery Charging**: Real-time calculations with MPPT technology can optimize battery charging efficiency. By monitoring energy production from the solar panels and the state of charge of the batteries, MPPT controllers can adjust charging parameters to maximize efficiency. For instance, during periods of high solar generation, the controllers can increase the charging rate to fully utilize available energy, enhancing the reliability of the energy supply in FMWH Mabuchi.

Incorporating real-time calculations and MPPT technology into the solar mini-grid system in FMWH Mabuchi would lead to tangible improvements in energy harvesting efficiency, grid stability, and battery charging optimization, ultimately achieving the objectives of the study.

To determine the addition to the original 1.52 MW of electricity produced by the solar panels in FMWH Mabuchi due to MPPT optimization, we can calculate the additional energy output gained from each solar panel and then sum up the total additional energy output for all panels.

Given:

- Total electricity produced by solar panels before MPPT optimization: 1.52 MW
- Capacity of each solar panel before MPPT optimization: 0.383 kW (as calculated previously)

Let's calculate the additional energy output gained from each solar panel with MPPT optimization:

Additional energy output per panel = 10% × Capacity of each solar panel

Additional energy output per panel = 0.10×0.383 Kw

Additional energy output per panel = 0.0383 kW

Now, let's calculate the total additional energy output for all panels:

Total additional energy output for all panels = Additional energy output per panel × Total number of solar panels

Total additional energy output for all panels = 0.0383 kW×3968

Total additional energy output for all panels ≈ 152.07 kW

So, with MPPT optimization, the additional energy output gained from the solar panels in FMWH Mabuchi would be approximately 152.07 kW.

4.1 Discussion of Results

The analysis of the adoption of solar mini-grid systems interconnected with the main grid for the FMWH Mabuchi project in Nigeria yields significant insights into the potential benefits and challenges of such systems. The study focused on the integration of 3,968 photovoltaic (PV) solar panels and 4,053 lithium-ion batteries, coupled with the implementation of Maximum Power Point Tracking (MPPT) technology. The results highlighted the technical, economic, and social dimensions of this approach to enhancing energy access and sustainability in urban areas.

Technical Analysis

Solar Panel and Battery Specifications:

- The 3,968 PV solar panels, each with an average power rating of 383 watts, collectively generated approximately 1.52 MW of electricity.
- The 4,053 lithium-ion batteries, each with a capacity of 10 kWh and a nominal voltage of 400 volts, provided a total energy storage capacity of 40.53 MWh.

Energy Production and Storage:

- The total daily energy production from the solar panels was put at 36.48 MWh.
- Considering the battery efficiency of 90%, the total energy required to be stored is approximately 40.53 MWh, which aligns with the capacity of the installed battery bank.

MPPT Implementation:

- MPPT technology optimizes the efficiency of the solar panels by ensuring they operate at their maximum power point (MPP) under varying environmental conditions.
- With MPPT, each solar panel gained an additional 10% in energy output, leading to an additional 152.07 kW in total energy output for the entire solar array.

Economic and Social Impact

Cost Efficiency:

- The integration of solar mini-grid systems with MPPT reduced reliance on traditional energy sources, lowering energy costs in the long term.
- The reduced dependence on the main grid and diesel generators will contribute to significant cost savings, particularly in energy-scarce regions.

Reliability and Stability:

- The enhanced reliability and stability of the energy supply due to grid interconnectivity and MPPT mitigate the intermittency of solar power, providing a more stable and resilient energy system.
- Continuous optimization of power output and battery charging through MPPT ensures a consistent energy supply, even during periods of low solar irradiance or grid outages.

Energy Access:

- Improved energy access and reliability directly impact the socio-economic development of urban areas, fostering economic opportunities and enhancing the quality of life.
- Increased electricity availability reduces the reliance on traditional fuels, promoting cleaner energy alternatives and contributing to environmental sustainability.

Case Study: FMWH Mabuchi

The Federal Ministry of Works and Housing (FMWH) in Mabuchi, Abuja, serves as an illustrative example of the effectiveness of integrating mini-grid solar energy resources with the main grid. The following outcomes were observed:

1. **Improved Power Generation:**
    - The integration of 1.52 MW of solar power, augmented by an additional 152.07 kW through MPPT, significantly enhances power generation capacity.
    - This increased capacity addresses the energy deficit and meets the growing demand in the rapidly urbanizing FMWH Mabuchi.
2. **Reduced Energy Costs:**
    - The shift from high-cost energy sources to solar energy reduces overall energy expenditure.
    - The cost savings are particularly notable in periods of peak demand and during outages when the reliance on expensive diesel generators is minimized.
3. **Enhanced Energy Access:**
    - Reliable and consistent electricity supply improves access to energy, particularly in peri-urban and rural extensions of the urban center.
    - The socio-economic benefits include improved healthcare services, educational facilities, and commercial activities, driven by stable energy access.

Limitations and Future Work

Data Availability:

- The study encountered limitations in the availability of long-term performance data for solar mini-grid systems in similar contexts, necessitating further research to assess long-term economic viability and environmental impact.

System Maintenance and Scalability:

- Challenges related to system maintenance, limited scalability, and uncertainties in revenue collection models were identified as areas requiring attention for the sustainable deployment of solar mini-grid systems.

Regulatory Frameworks:

- The study highlights the need for supportive regulatory frameworks to facilitate grid integration and market competitiveness of solar mini-grid systems. Addressing policy gaps and enhancing institutional capacities are crucial for successful implementation.

In conclusion, the integration of mini-grid solar energy resources with the main grid in urban areas like FMWH Mabuchi, Nigeria, presents a viable solution to the persistent energy deficit. The adoption of MPPT technology further optimizes energy production, enhancing reliability, efficiency, and access. This study provides valuable insights into the technical and economic feasibility of such systems, underscoring their potential to drive sustainable energy development in developing countries. Future research should focus on long-term performance assessment, maintenance strategies, and the development of robust regulatory frameworks to support widespread adoption.

5.1 Conclusion

The integration of solar mini-grid systems interconnected with the main grid in urban areas, exemplified by the FMWH Mabuchi project in Nigeria, demonstrates significant potential for enhancing energy access and sustainability. This study, focusing on the technical, economic, and social dimensions, reveals that the deployment of 3,968 photovoltaic (PV) solar panels and 4,053 lithium-ion batteries, coupled with Maximum Power Point Tracking (MPPT) technology, can substantially improve power generation, reduce energy costs, and enhance reliability.

Technically, the solar panels and batteries provided substantial energy output and storage capacity, addressing the energy deficit in rapidly growing urban areas like FMWH Mabuchi. The implementation of MPPT technology resulted in a notable increase in energy output, optimizing the efficiency of the solar panels and contributing an additional 152.07 kW to the overall power generation.

Economically and socially, the integration of solar mini-grid systems with MPPT reduced reliance on traditional and costly energy sources, fostering long-term cost savings and promoting environmental sustainability. The improved reliability and stability of the energy supply have direct positive impacts on socio-economic development, enhancing the quality of life and economic opportunities in the urban center.

Despite the promising outcomes, the study identifies areas requiring further attention, such as the availability of long-term performance data, system maintenance challenges, scalability, and the need for supportive regulatory frameworks. Addressing these limitations is crucial for the sustainable deployment and widespread adoption of solar mini-grid systems in developing countries.

To sum up, the integration of mini-grid solar energy resources with the main grid in urban areas like FMWH Mabuchi offers a viable and sustainable solution to persistent energy deficits. By optimizing energy production and enhancing grid reliability, such systems have the potential to drive sustainable energy development, improve energy access, and foster socio-economic growth in developing countries. Future research should continue to explore long-term performance, maintenance strategies, and regulatory support to ensure the success and scalability of these systems.

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