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ENHANCING MICROGRID EFFICIENCY: AN OPTIMIZATION APPROACH FOR SOLAR PV AND ENERGY STORAGE MANAGEMENT

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ABSTRACT

This paper presents a cost-effective Energy Management System (EMS) designed for microgrids integrating renewable solar energy and Superconducting Magnetic Energy Storage (SMES). The microgrid, simulated using MATLAB/Simulink, features photovoltaic (PV) panels for power generation and an energy storage system (ESS) to manage surplus energy. The study analyses two weather conditions—clear and cloudy days—using real-time datasets to assess the system's performance. Two case studies were conducted: the first under clear day conditions, and the second under cloudy day conditions. Simulation results show fluctuations in Microgrid voltage and active power generation between PV, ESS, the grid, and loads. By applying a linear programming-based optimization approach, the EMS effectively manages the charging and discharging cycles, ensuring cost savings. Results demonstrate that under clear day conditions, the cost per day is reduced from $730 (without optimization) to $615 using the optimization approach while maintaining stable grid operations. Similar cost reductions are observed under cloudy day conditions, highlighting the superiority of optimization over heuristic methods. This work demonstrates the feasibility of using hybrid solar-SMES systems for efficient energy management in microgrids, providing optimized power generation and storage solutions while minimizing operational costs.

Keywords: Energy Management System, Microgrid, Photovoltaic System, SMES, Hybrid Power System, Optimization Techniques.

I. INTRODUCTION

The growing global demand for energy, coupled with environmental concerns, has spurred a significant shift toward the integration of renewable energy sources (RES) into modern power grids. Traditional power systems, which rely predominantly on fossil fuels, are not only inefficient but also contribute to greenhouse gas emissions and environmental degradation. As a result, the energy sector is undergoing a rapid transformation toward more sustainable solutions, with renewable energy sources such as solar, wind, and hydropower playing a key role [1]. Among these, **solar energy** has emerged as a highly promising resource due to its abundance and scalability. However, integrating renewable sources into the power grid brings its own set of challenges, primarily due to the intermittent and variable nature of these resources [2]. This necessitates the development of robust **Energy Management Systems (EMS)** that ensure a reliable, stable, and cost-effective supply of power, especially in systems like **microgrids (MGs)[3]**.

Microgrids are localized energy systems that incorporate both power generation and consumption within a small area, making them ideal for the decentralized integration of renewable energy. They can operate in both grid-connected and standalone modes, providing flexibility to optimize energy usage based on demand and supply conditions. One of the key components of microgrids is an **Energy Storage System (ESS) [4]**, which is essential for storing excess power generated from RES for later use, especially when the renewable source is unavailable or insufficient due to environmental factors such as cloudy or rainy conditions.

The concept of a **hybrid power system** further enhances microgrid efficiency by combining different energy sources, such as solar energy and ESS, to ensure a continuous supply of power. This paper focuses on the integration of **Photovoltaic (PV)** solar panels with **Superconducting Magnetic Energy Storage (SMES)** in a hybrid power system [5]. The variability in solar power output due to changing weather conditions, such as clear and cloudy days, presents challenges in maintaining a stable power supply. To address these issues, the hybrid system uses SMES for dynamic energy storage and power management, enabling smooth power delivery under fluctuating solar generation conditions.

In this study, a hybrid Microgrid model is developed using **MATLAB/Simulink**, incorporating solar energy generation, an ESS for energy storage, and different types of loads (fixed and variable). The model is tested under two case studies, clear day and cloudy day scenarios which affect the energy generation and consumption dynamics differently. To optimize the system's performance, both **heuristic and optimization-based approaches** are employed, ensuring the cost-effective operation of the Microgrid. This research highlights the importance of optimizing energy management in microgrids to minimize operational costs, particularly by focusing on energy storage and efficient load distribution.

II. LITERATURE REVIEW

BASIC CONCEPTS

The integration of renewable energy sources into the electrical grid has been an area of significant research interest due to the increasing demand for sustainable and eco-friendly power generation. Renewable Energy Sources (RES) such as solar, wind, and hydro have been considered as alternative solutions to traditional fossil-fuel-based generation methods. However, the inherent variability and unpredictability of RESs, especially solar energy, introduce a range of operational challenges. To address these challenges, researchers have proposed various strategies, including Energy Management Systems (EMS), hybrid power systems, and advanced energy storage technologies.

2.1 Energy Management Systems (EMS) for Microgrids

Microgrids (MGs) have emerged as a critical element of modern electrical networks, particularly in regions with high penetration of renewable energy sources. EMS in microgrids plays a vital role in monitoring, controlling, and optimizing energy generation, storage, and consumption to achieve reliable and efficient operation. As noted by Uddin et. al. [6], EMS enables the seamless integration of renewable sources into the grid while ensuring stability, especially in off-grid or islanded microgrids.

Recent studies emphasize the importance of advanced EMS designs that incorporate real-time decision-making mechanisms for managing power flows between energy sources, storage systems, and loads. For instance, Hao Tian et al. [7] 2022 explored a multi-objective optimization-based EMS to minimize operational costs while maximizing the use of renewable energy. In contrast, S Jamal et. al. [8] investigated a heuristic-based approach for EMS design, focusing on rule-based methods to manage power flows between sources and energy storage systems as shown in Figure 1, the basic flow of EMS in a microgrid.

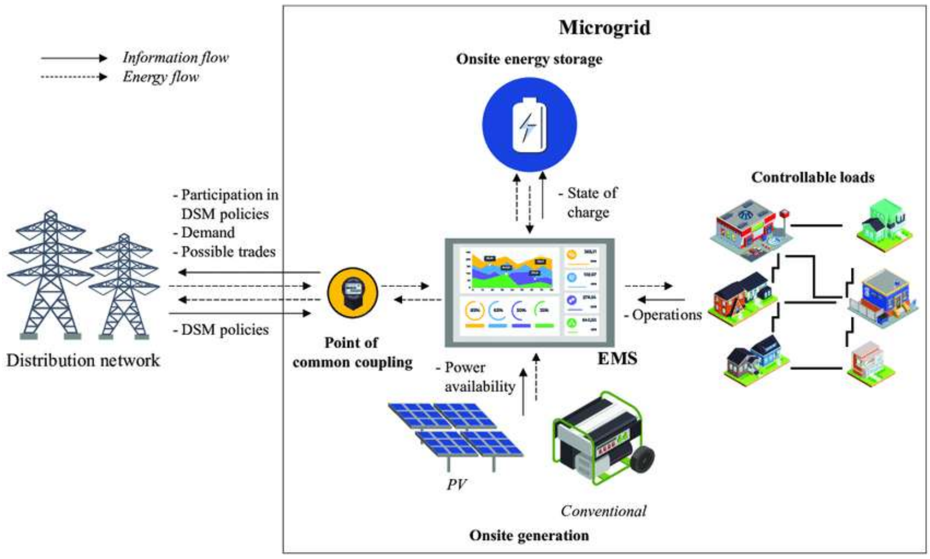

Figure 1: The basic flow of EMS in a microgrid

The hybridization of EMS with optimization techniques has gained popularity in recent research. Studies have shown that employing linear programming (LP) and other optimization algorithms significantly enhances EMS performance by reducing costs and improving energy efficiency

2.2 Hybrid Power Systems with Solar Energy

Solar Photovoltaic (PV) technology [2] has been one of the most widely used renewable energy sources in microgrids, primarily due to its abundant availability and ease of deployment. However, solar energy generation is highly dependent on weather conditions, which leads to fluctuations in power output.

To mitigate these challenges, researchers have proposed the use of hybrid systems that combine solar PV with energy storage technologies. One of the most effective solutions has been the use of Superconducting Magnetic Energy Storage (SMES). SMES systems store energy in the magnetic field created by a superconducting coil, offering fast response times and high energy efficiency. A. Bakeer et. al. [9] demonstrated the effectiveness of integrating SMES into a solar-powered microgrid, reducing fluctuations in energy supply and improving system stability.

2.3 Superconducting Magnetic Energy Storage (SMES)

SMES has been gaining attention due to its unique advantages over other storage technologies like batteries. Unlike traditional battery systems, which suffer from slow response times and gradual degradation, SMES offers virtually instantaneous energy release and long operational lifespans. Jin, J. X et al. [10], SMES has been successfully applied in microgrid configurations to manage voltage and frequency fluctuations, which are common in solar-powered systems.

The use of SMES in hybrid power systems has also shown significant improvements in terms of both power quality and system reliability. Amit et. al. [11] presented a case where SMES helped stabilize a PV-dominated microgrid during sudden drops in solar generation, such as on cloudy days. The fast-acting nature of SMES allowed the microgrid to continue operating smoothly without relying on grid power or diesel generators.

2.4 Optimization and Heuristic Approaches in Energy Management

Research into optimization techniques for EMS has been growing, with numerous studies focused on minimizing energy costs, enhancing efficiency, and ensuring reliable power delivery in hybrid microgrid systems. As outlined by Fedjaev J et. al. [12], Linear Programming (LP) has emerged as a powerful tool for optimization-based EMS. LP-based approaches optimize energy usage by considering constraints such as generation capacity, load demands, and storage availability, making them highly effective in hybrid systems with intermittent power generation sources.

Heuristic methods, on the other hand, are often employed in real-time EMS applications where computational simplicity and speed are critical. While heuristic approaches may not always provide globally optimal solutions, they are practical for real-time energy management scenarios. Thirunavukkarasu et. al. [13] applied a rule-based heuristic approach to manage energy flows in a solar-based Microgrid, achieving reasonable cost reductions without the complexity of full-scale optimization models.

2.5 Case Studies and Simulation Results

Various case studies have been conducted to demonstrate the effectiveness of hybrid solar-ESS systems in microgrids. Xia et al. [14] performed a simulation of a PV-SMES hybrid system under two different weather conditions: a clear day and a cloudy day. The simulation results indicated that while solar output fluctuated significantly under cloudy conditions, the integration of SMES helped stabilize the system, preventing voltage drops and power shortages.

In another study by Shufian A. et. al. [15] a cost-effective analysis was conducted using heuristic and optimization-based EMS approaches. The findings revealed that the optimized EMS system reduced energy costs by 15% under clear day conditions and 10% under cloudy day conditions compared to the heuristic method.

III. PROPOSED METHODOLOGY

The reliance on conventional energy sources such as coal, natural gas, and crude oil leads to higher electricity production costs and environmental pollution. Since the 1970s oil crisis, renewable energy sources like solar, wind, and biomass have gained significant attention due to their potential to produce electricity without pollution. Fossil fuels, being non-renewable, are also inefficient and contribute heavily to global warming. Additionally, the future scarcity of fossil fuels has spurred interest in clean energy alternatives.

Renewable energy reduces carbon emissions and chemical pollutants while offering economic benefits. However, the variability of renewable resources requires a hybrid energy generation approach, combining multiple sources for stability. For example, solar and wind energy can complement each other under varying conditions. Weather factors, such as radiation and wind, play a critical role in power generation. Research has increasingly focused on optimizing hybrid renewable systems for reliable and sustainable energy, such as wind-hydro and solar-hydro combinations, ensuring better energy supply and system reliability.

3.1 Photovoltaic Cell

A photovoltaic (PV) panel or solar cell converts solar energy directly into electrical energy using the photovoltaic effect. It consists of a photoelectric cell whose electrical characteristics change under sunlight, forming the basis of PV modules. The incident radiation and temperature play a key role in generating photocurrent [17].

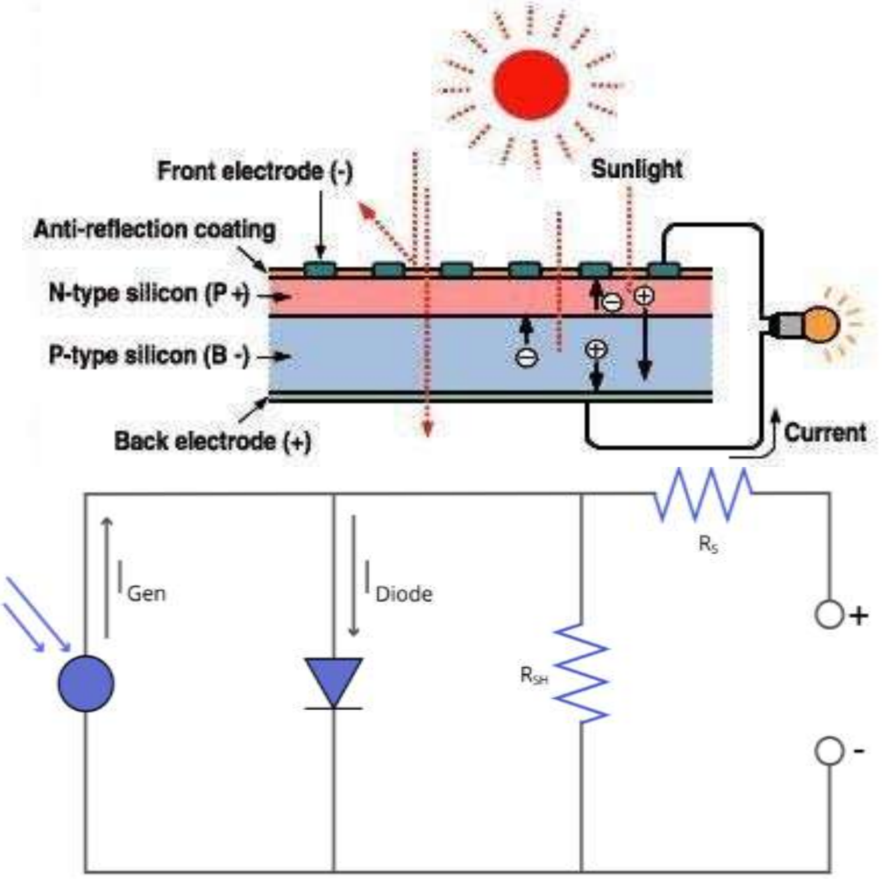

Figure 2: (a) Schematic diagram of the solar cell, (b) The equivalent circuit.

Figure 2(a) shows the solar cell schematic, while Figure 2(b)presents the equivalent circuit. The diode represents the p-n junction, and system modeling considers constant diode parameters and the temperature dependence of the saturation current. Voltage losses are modeled with series resistance. R_s, and parallel resistance R_{sh} accounts for leakage currents, often neglected due to their small values.

The current equation of a PV cell is:

$$I_{pv}(t) = I_{sc}\left(1 - C_1\left[\exp\left(\frac{V_{mp}}{C_2 V_{oc}}\right) - 1\right]\right) + \left(\frac{E_{tt}(t)}{E_{st}}\right)[\alpha(T_a(t) + 0.002E_{tt}(t) + 1)] - I_{mp}$$

The voltage equation is:

$$V_{pv}(t) = V_{mp}\left(1 + 0.0539\log\left(\frac{E_{tt}(t)}{E_{st}}\right)\right) + \beta(T_a(t) + 0.02E_{tt}(t))$$

These equations were used to create a solar cell model in MATLAB/Simulink. Figure 3 shows the internal model of the solar cell.

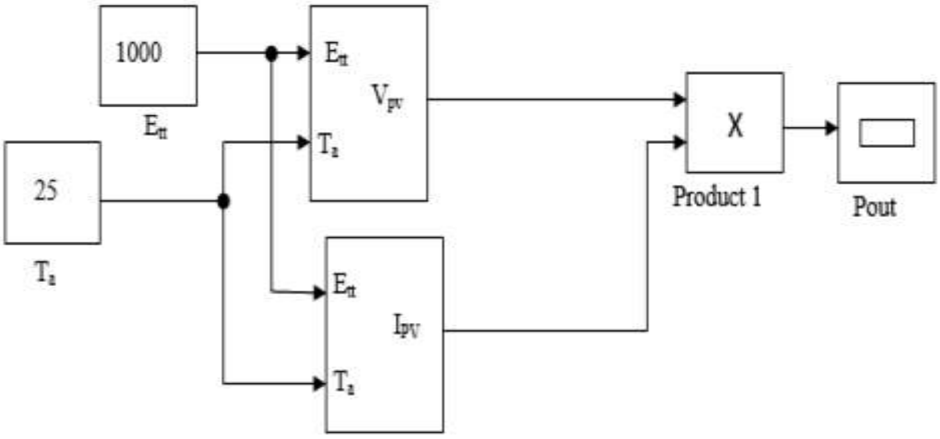

Figure 3: Solar Cell Internal Model

3.2 Maximum Power Point Tracking (MPPT)

Traditional PID controllers are unsuitable for MPPT due to system nonlinearity. Fuzzy logic control (FLC) can manage power and voltage, but it adds complexity and may not be optimal, especially for high-inertia wind turbines. The input-output feedback linearization method (Figure 4) addresses these issues, optimizing variable-speed wind turbines (VSWT). An adaptive controller enhances performance by optimizing torque and rotor speed. A hybrid wind/PV system with CUK and Spice converters is proposed, allowing:

- Step-up/step-down operation
- Effective MPPT for both sources
- Reduced need for input filters
- Smooth dynamic performance

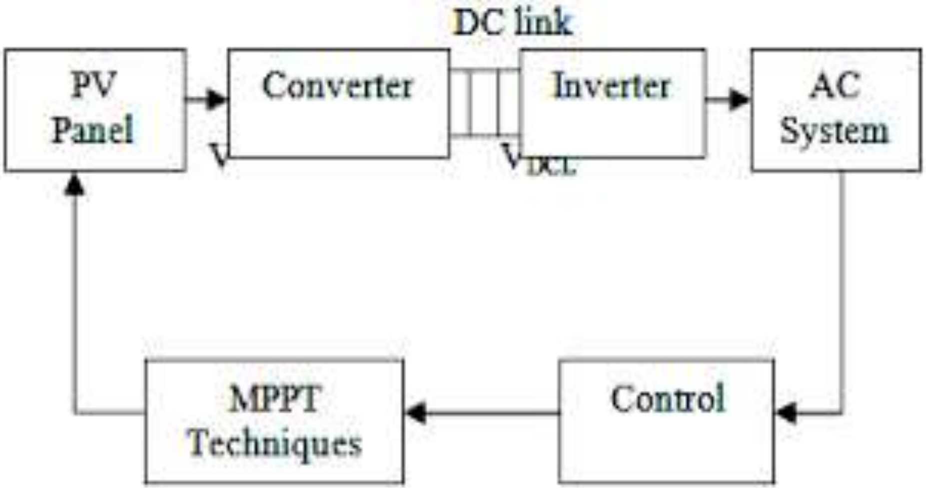

Figure 4: Proposed MPPT system schematic.

3.2.1 Superconducting Magnetic Energy Storage (SMES)

SMES addresses output voltage fluctuations in power systems relying on intermittent sources by storing energy during low demand and supplying it during high demand. A two-quadrant DC-DC chopper and PWM voltage source converter provide smoother power output. SMES uses a superconducting coil that stores energy as a magnetic field, requiring low temperatures to maintain superconductivity.

SMES offers quick charge/discharge cycles and high efficiency (>90%), outperforming alternatives like CAES and Li-ion batteries. However, it's more suitable for small applications due to the high cooling costs for larger systems.

3.2.2 Modelling of Proposed System with SMES

The proposed hybrid system integrates PV and SMES models, with controller-based SMES regulation. Figure 5 shows the SMES system, where output voltage and SMES coil current are monitored during simulation.

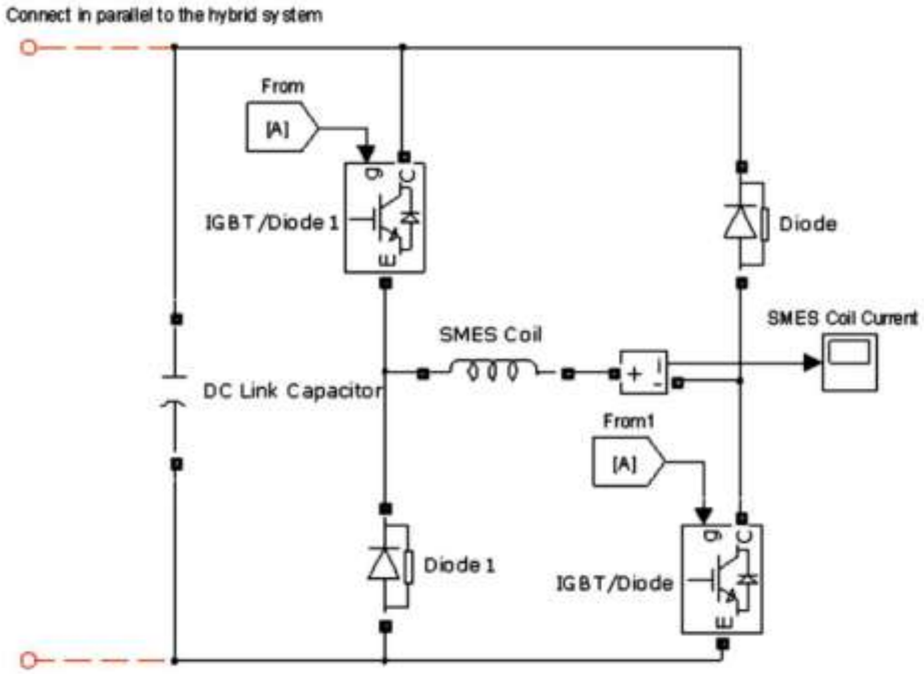

Figure 5: SMES System

3.3 Energy Storage System (ESS)

As demand for electrical power grows, renewable energy sources (RES) play a key role. However, since RES availability fluctuates with weather conditions, ESS is essential to meet consumer demand by balancing generation and storage in hybrid systems.

IV. SIMULATION AND ANALYSIS OF HYBRID POWER SYSTEM

4.1 Simulation Overview: This section of the paper covers the modeling and simulation of a hybrid power system, including solar cell modeling, an energy storage system (ESS) with battery charge/discharge concepts, and variable loads under clear and cloudy day conditions. A fixed load is also connected to the hybrid system. A cost-effective analysis of the system is performed. Hybrid solar-ESS power generation is promising, but environmental randomness poses challenges. To address voltage and frequency fluctuations, converters are utilized in solar cells and ESS.

4.2 Hybrid Power Generation System: In hybrid power generation, solar cell output varies based on sunlight and temperature. A battery bank is connected in parallel with the solar panels to compensate for any shortfall. The ESS manages energy storage during the day and powers load when solar energy is insufficient. The simulation considers both clear and cloudy day conditions for different load profiles.

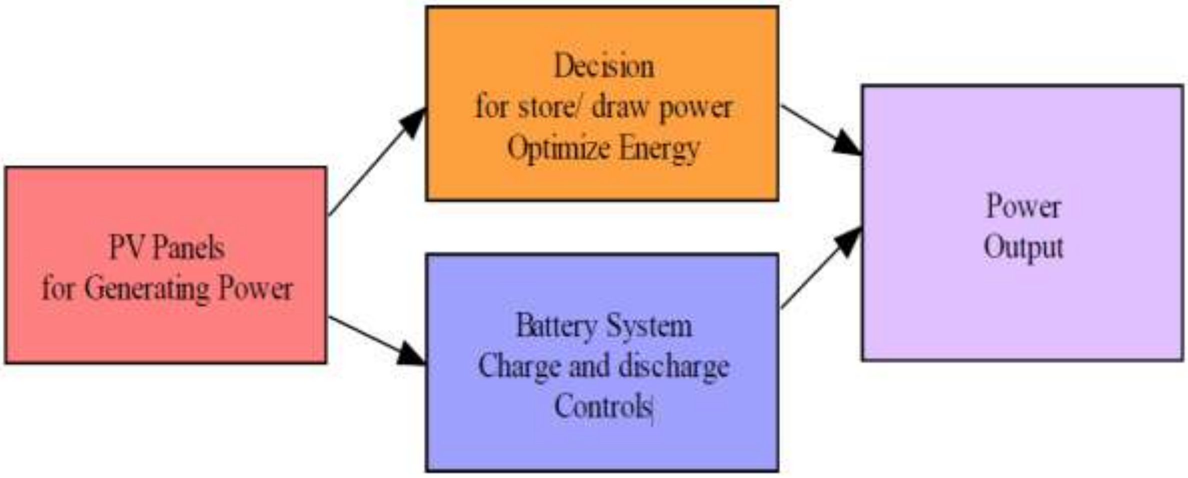

Figure 6: Proposed Hybrid System

4.3 Designing Renewable-based Microgrid

4.3.1 PV System Modelling: The PV system model uses a Superconducting Magnetic Energy Storage (SMES) coil regulator. Figure 7 shows the complete Simulink model connected to the grid.

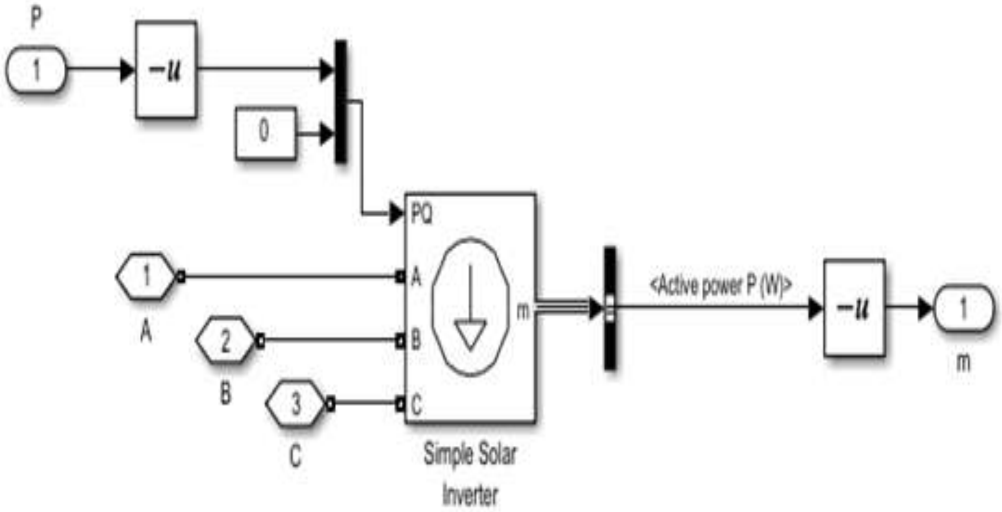

Figure 7: Simulink diagram of the solar system

4.3.2 Energy Storage System (ESS): ESS is crucial for energy management in the system. Solar power is stored for later use when not immediately available. Figure 8 shows the Simulink model of the ESS. The battery manages excess solar generation by charging during peak production and discharging during low production.

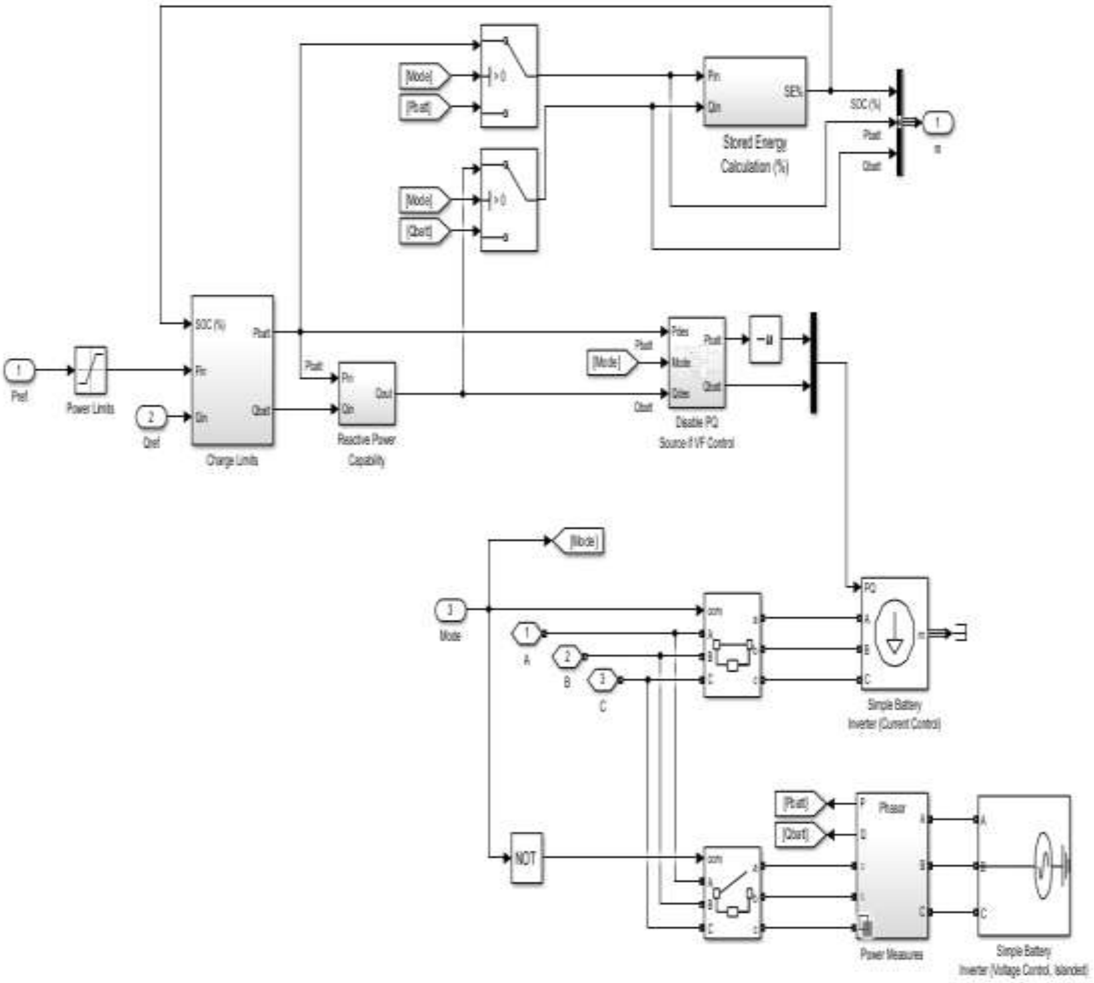

Figure 8: Simulink diagram of an energy storage system in MATLAB

4.3.3 Varying Load: A varying load is included alongside a constant load in this work. The load changes according to consumer demand, considering scenarios like clear and cloudy days. A fixed load of 3500 watts is connected to the system. Figure 9 shows the Simulink diagram of varying loads.

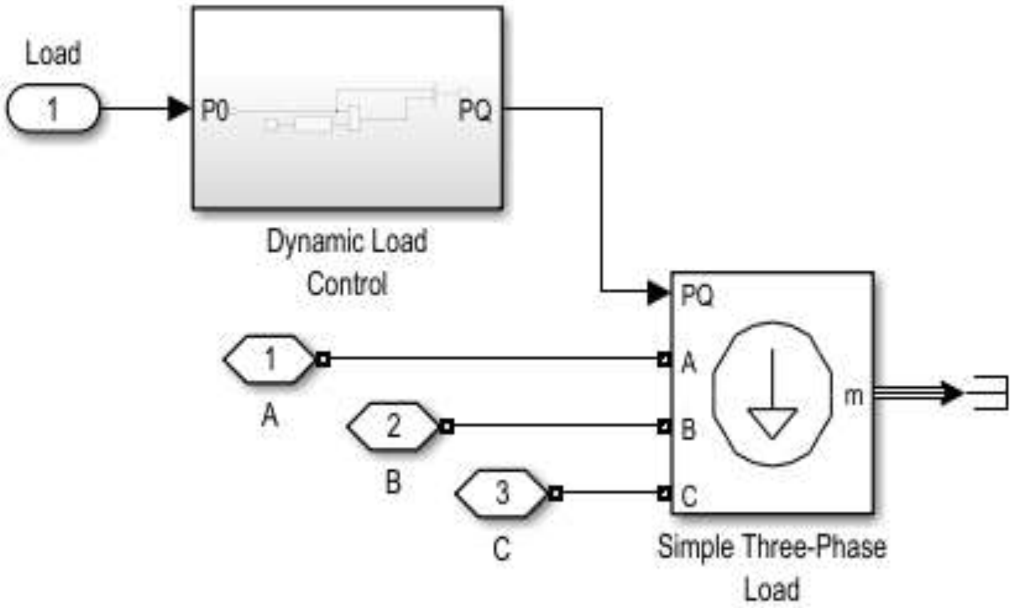

Figure 9: Varying load in Simulink

1.4 Forecasting Data for Analysis

The work uses various datasets for cost-effective analysis, including:

- Clear day dataset
- Cloudy day dataset
- Four types of load profiles

V. RESULTS AND DISCUSSION

A cost-effective energy management system (EMS) has been developed for managing power in microgrids. The system uses solar photovoltaic (PV) cells for power generation and an energy storage system (ESS) for storing excess energy.

The study focuses on analyzing two weather conditions—a clear day and a cloudy day—using MATLAB for simulation and modeling. The microgrid consists of:

- **PV Panels** for generating power
- **Energy Storage System (ESS)** for charging and discharging power
- **Variable and Constant Loads** (with fixed loading of 350 KW)

A hybrid system was developed in MATLAB, with a Simulink design for individual components.

The optimization approach used in this study applies linear programming to achieve more accurate and effective results for energy management.

Case I: Clear Day Simulation

In the clear day scenario, solar panels generate power that is sent to the ESS, charging and discharging as needed.

The energy management system performs cost analysis, revealing an initial cost per unit of $730, which is reduced to $615 after optimization.

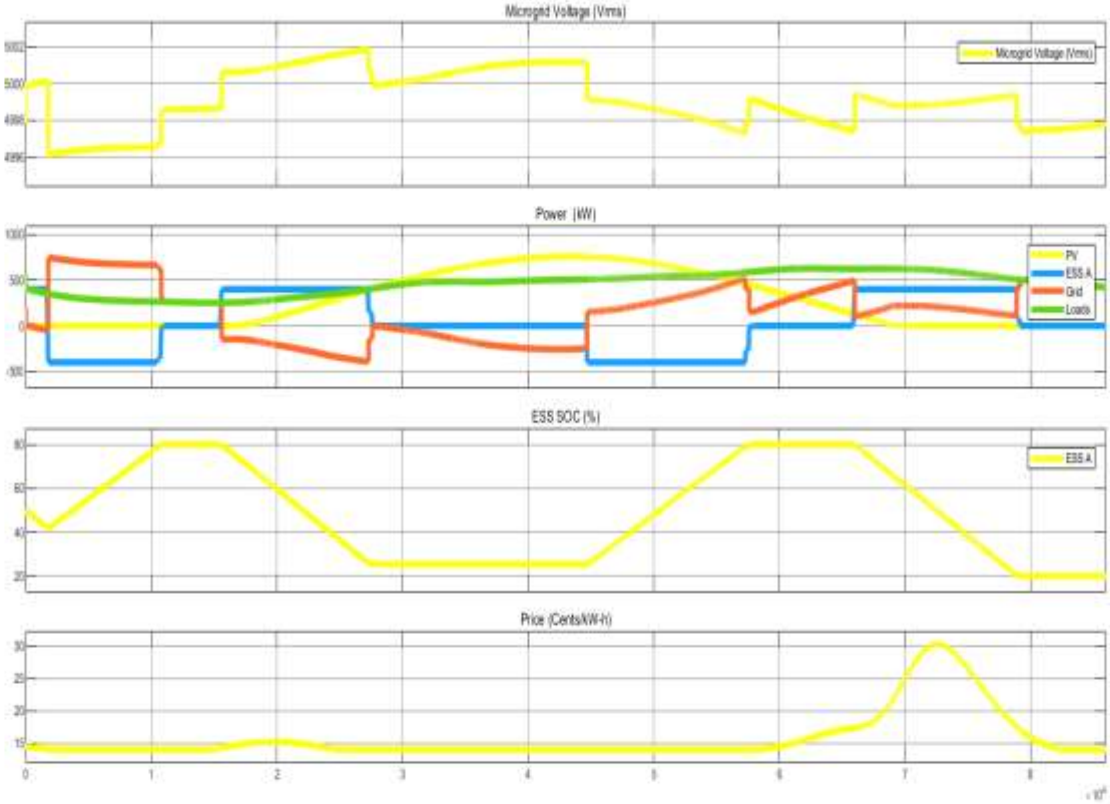

Figure 10: Results obtained by optimization approach in clear day weather conditions

Figure 10 shows the simulation results for clear day conditions, highlighting voltage, power fluctuations (PV, ESS, Grid, Load), ESS charging state, and cost per kWh.

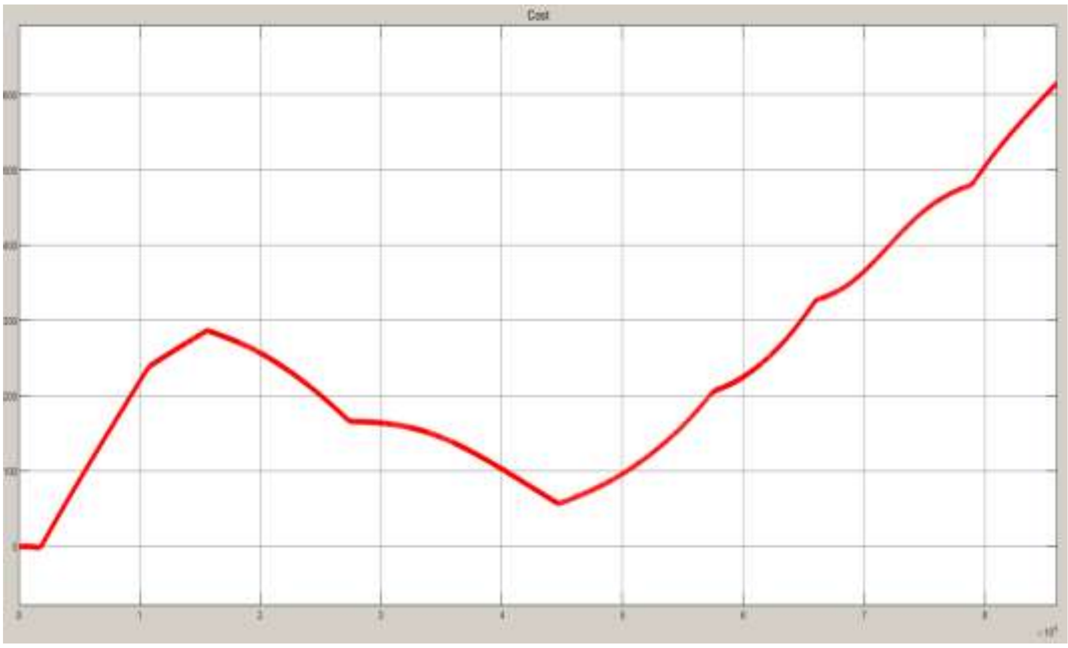

Figure 11: Effective cost analysis using an optimization approach

Figure 11 presents the cost analysis under clear day conditions, where optimization reduces costs significantly.

Case II: Cloudy Day Simulation

The cloudy day scenario follows the same methodology as the clear day, with adjustments based on reduced solar output. The cost per unit in the cloudy day condition is also initially $730, but using the optimization approach, the cost is reduced to $615.

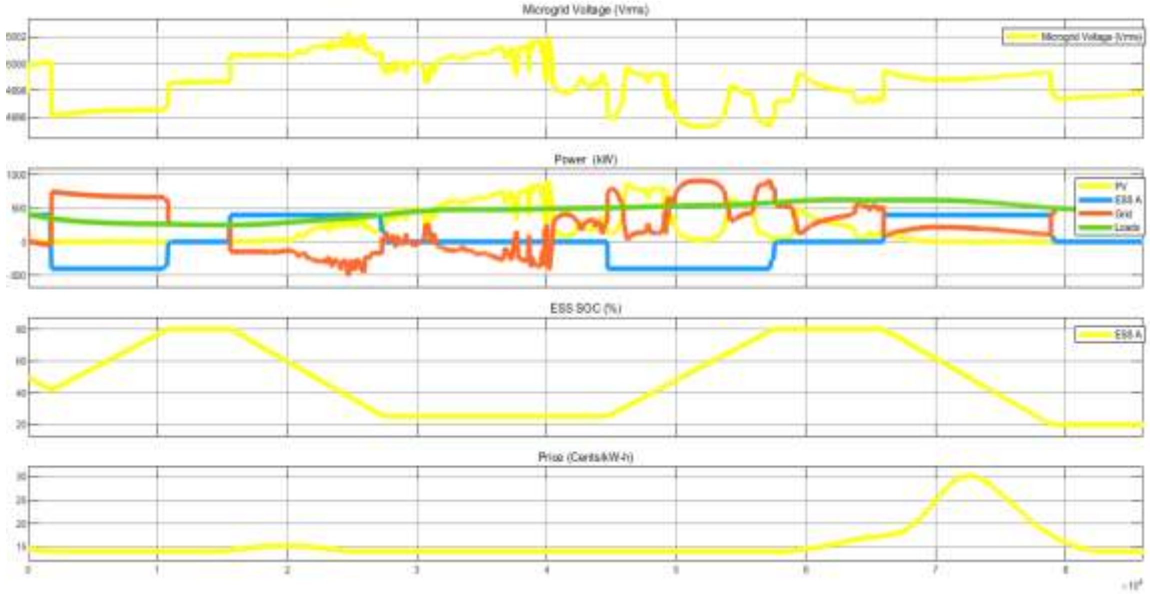

Figure 12: Simulation results considering the optimization approach for cloudy weather conditions

Figure 12 illustrates the simulation results under cloudy day conditions, showing similar fluctuations and outcomes as in the clear day case.

Comparative Analysis: Heuristic vs. Optimization

A comparative analysis between heuristic and optimization-based approaches was conducted. Results show that the optimization method significantly reduces both grid usage and cost over 24 hours compared to the heuristic approach.

Figure 13 highlights the cost comparison between heuristic and optimization methods for both clear and cloudy day conditions.

The experiments and results demonstrate that using a linear programming-based optimization approach for energy management in microgrids reduces energy costs and grid dependency more effectively than heuristic methods. The combination of solar energy and energy storage provides an efficient solution for energy management in both clear and cloudy conditions.

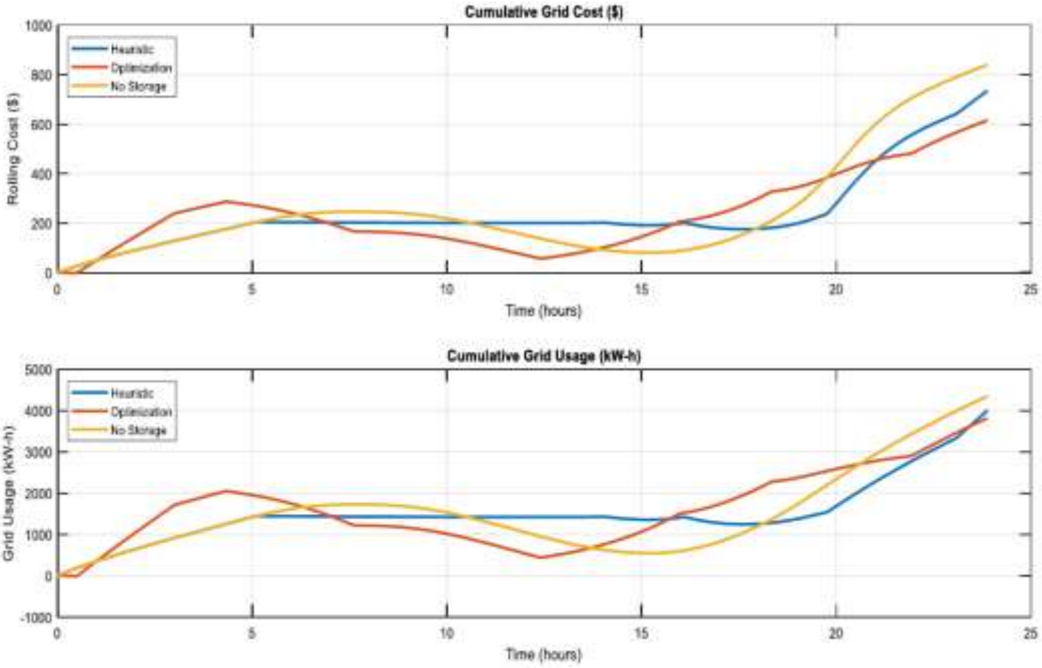

Figure (a)

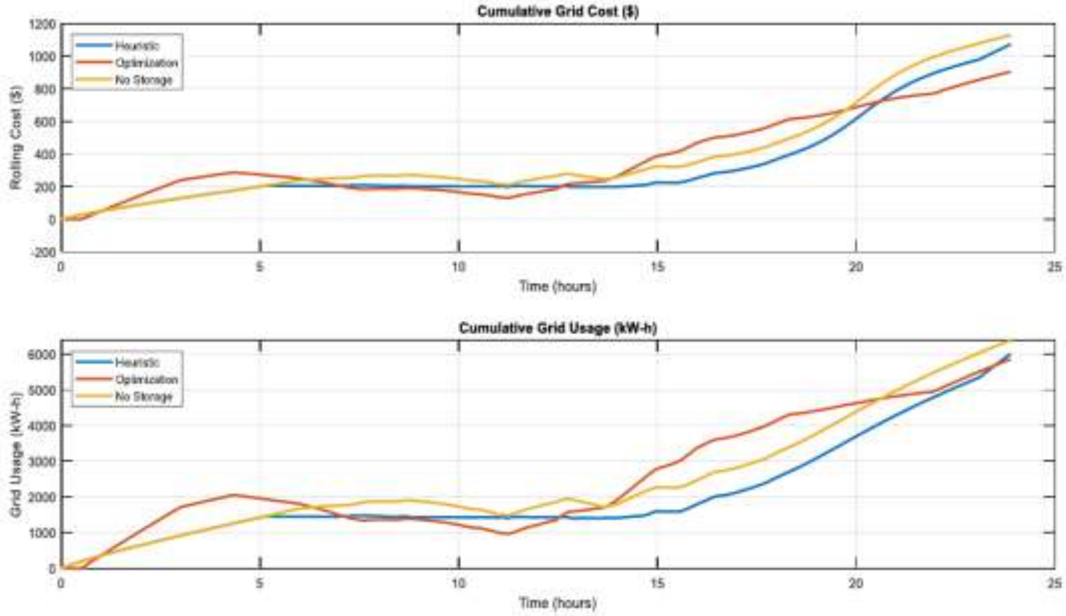

Figure (b)

Figure 13: Comparative analysis for grid cost and grid usage between optimized and heuristic-based approach (a) Clear Condition (b) Cloudy Condition

VI. CONCLUSION

In this work, a cost-effective energy management system (EMS) for microgrids has been designed and implemented using MATLAB/Simulink. The proposed system integrates solar photovoltaic (PV) cells and an energy storage system (ESS) to ensure continuous power supply under varying weather conditions. Two case studies—clear day and cloudy day—were used to evaluate the performance of the system. The results demonstrate that effective energy management can significantly reduce operational costs, particularly when utilizing an optimization approach based on linear programming. The optimization reduced costs from $730 to $615 per day compared to heuristic methods, showcasing the potential of intelligent energy management for microgrids. This study also highlights the importance of ESS in compensating for the intermittent nature of solar power, ensuring stability in microgrid voltage and meeting load demands efficiently.

VII. FUTURE WORK

In the future, this work can be extended by integrating additional renewable energy sources such as wind and biomass to improve the reliability and performance of microgrids. Advanced energy storage technologies, such as fuel cells and Superconducting Magnetic Energy Storage (SMES), could be explored to enhance system efficiency. Real-time energy management using IoT and machine learning for demand forecasting and predictive control can further optimize operations. Additionally, incorporating demand-side management (DSM) strategies and examining grid interaction for scalability in larger applications will be essential. Future research can also focus on dynamic pricing models to refine cost analysis and develop more adaptive, cost-effective energy management systems for practical use.

These future directions will help advance the field of renewable energy management systems, enabling more resilient, cost-effective, and sustainable energy solutions for microgrids.

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