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A Review On Solar PV Based Microgrid System For Sustainable Power Supply In Commercial Buildings

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Abstract
The increasing energy demand in commercial buildings and growing environmental concerns have accelerated the adoption of renewable energy technologies. Solar photovoltaic (PV) systems integrated with microgrids offer a sustainable solution for reliable and efficient power supply. This study proposes a Solar PV-based microgrid system equipped with an Energy Management System (EMS) to ensure continuous and optimized electricity supply in commercial buildings. The system incorporates Maximum Power Point Tracking (MPPT) using the hill-climbing algorithm to maximize PV energy extraction under varying irradiance conditions. A Battery Energy Storage System (BESS) is integrated to store surplus energy and provide backup during nighttime or low solar availability. Loads are categorized into secured and non-secured types, with an Uninterruptible Power Supply (UPS) ensuring uninterrupted power to critical loads during grid outages. The EMS intelligently manages energy flow between PV generation, battery storage, and grid supply under grid-connected and standalone modes. Simulation results demonstrate improved energy efficiency, enhanced reliability, reduced dependence on fossil fuels, and sustainable energy utilization in commercial building applications.

Keywords: Solar Photovoltaic (PV) System, Microgrid Energy Management System (EMS), Maximum Power Point Tracking (MPPT), Battery Energy Storage System (BESS), Sustainable Commercial Building Energy etc.

1. Introduction

Rapid urbanization and technological growth have significantly increased electricity demand, particularly in commercial buildings such as shopping complexes, hospitals, educational institutions, and office infrastructures. These buildings consume substantial electrical energy for lighting, heating, ventilation, air conditioning (HVAC), elevators, computing systems, and security operations. Traditionally, this energy demand has been met through fossil-fuel-based power generation, which contributes to greenhouse gas emissions, environmental degradation, and rising operational costs [1].

The global push toward sustainable energy solutions has encouraged the integration of renewable energy sources into power systems. Among these sources, solar photovoltaic (PV) energy has emerged as one of the most promising alternatives due to its abundance, environmental friendliness, and decreasing installation costs [2]. Solar energy is widely available across most geographic regions, making it a viable option for decentralized electricity generation in commercial infrastructures.

Despite its advantages, the use of solar energy in commercial buildings remains limited, often restricted to small-scale applications such as water heating or partial lighting systems. One major limitation of PV systems is their intermittent nature, as electricity generation depends on solar irradiance and is unavailable during nighttime or cloudy conditions [3]. This variability creates challenges in maintaining continuous power supply for buildings that require uninterrupted electricity for critical operations.

To overcome these limitations, microgrid technology has gained attention as an effective solution for integrating distributed energy resources (DERs), including PV systems and energy storage devices. A microgrid is a localized energy network capable of operating in grid-connected or standalone modes, ensuring reliable power supply and improved energy efficiency [4]. By integrating solar PV generation with battery energy storage systems (BESS), excess energy generated during the daytime can be stored and utilized during periods of low solar availability, ensuring 24×7 electricity supply.

Energy Management Systems (EMS) play a vital role in optimizing microgrid performance by balancing energy generation, storage, and consumption. EMS controls power flow between PV systems, batteries, loads, and the utility grid to ensure efficient operation and energy conservation [5]. Intelligent EMS strategies help reduce energy losses, improve system stability, and optimize load scheduling based on energy availability and demand patterns.

Another critical component in PV systems is Maximum Power Point Tracking (MPPT), which maximizes energy extraction from solar panels under varying environmental conditions. MPPT algorithms such as hill climbing, perturb and observe, and incremental conductance enhance system efficiency by continuously adjusting operating parameters to track the maximum power point [6]. Effective MPPT implementation significantly improves PV system performance, especially under fluctuating irradiance and temperature conditions.

Commercial buildings often require prioritization of loads to maintain essential operations during power interruptions. Categorizing loads into secured (critical) and non-secured (non-critical) loads enables intelligent load management. Critical loads such as emergency lighting, medical equipment, and security systems require uninterrupted supply, which can be ensured using Uninterruptible Power Supply (UPS) systems integrated within the microgrid framework [7].

This study proposes a Solar PV-based microgrid system with an advanced EMS designed to enhance energy reliability, efficiency, and sustainability in commercial buildings. The proposed system integrates PV generation, MPPT control, battery storage, UPS backup, and intelligent load prioritization to ensure continuous power supply. The EMS dynamically manages power distribution under grid-connected and standalone modes, optimizing energy utilization while reducing reliance on conventional grid electricity.

The implementation of such smart microgrid systems contributes to reducing carbon emissions, minimizing transmission losses, and promoting sustainable energy adoption in commercial infrastructures [8]. By improving reliability and efficiency, PV-based microgrids represent a practical and scalable solution for future smart energy systems.

2.Problem Identification

The rapid increase in electricity demand within commercial buildings has intensified dependence on fossil-fuel-based grid power, leading to higher carbon emissions and environmental degradation [1]. Although solar photovoltaic (PV) energy is abundant and sustainable, its adoption in commercial infrastructure remains limited and underutilized [2]. One of the major challenges associated with PV systems is their intermittent nature, as power generation depends on solar irradiance and is unavailable during nighttime or adverse weather conditions, resulting in unreliable supply [3]. Additionally, the absence of efficient energy storage systems restricts the utilization of excess solar energy for later use [4]. Integrating distributed PV generation with existing power distribution networks is complex due to fluctuating generation and varying load demands [5]. Commercial buildings also lack intelligent energy management and load prioritization mechanisms to ensure uninterrupted power for critical operations [6]. Consequently, inefficient energy utilization, increased operational costs, and continued reliance on conventional grid electricity persist [7].

3.Literature Survey

A) Literature Review

Eyimaya, S. E. (2024), This review presents a comprehensive comparative analysis of different Energy Management System (EMS) strategies used in microgrids. It examines classical control methods, meta-heuristic optimization techniques, artificial intelligence-based approaches, and model predictive control. The study highlights how these strategies address the challenges of integrating variable renewable energy sources, such as solar and wind, into microgrids while maintaining system stability and efficiency. Emphasis is placed on balancing supply and demand, minimizing energy losses, and optimizing the performance of distributed generation and storage units. The findings demonstrate that effective EMS is essential for reliable, sustainable microgrid operation.

Sandeep, S. D. (2025), The study investigates control strategies and Energy Management Systems (EMS) specifically for DC microgrids, emphasizing their importance in improving efficiency, reliability, and overall system performance. It highlights the key benefits of EMS, including optimized energy flow, effective load management, and enhanced stability under varying operational conditions. The research also addresses the challenges associated with integrating renewable energy sources, such as solar PV and wind, along with energy storage systems, into DC microgrids. Furthermore, it explores techniques to balance power generation and consumption, minimize energy losses, and ensure seamless operation in both grid-connected and standalone modes.

Sakib, S. (2025), This study focuses on Battery Energy Storage Systems (BESS) and their integration into Energy Management System (EMS) frameworks within microgrids. It reviews various BESS control strategies, highlighting their role in maintaining grid stability and improving power quality. The research emphasizes how effective management of energy storage can mitigate the variability of renewable energy sources, ensuring a reliable and continuous power supply. By optimizing the operation of batteries alongside distributed generation units, the study demonstrates the potential for enhanced efficiency, reduced energy losses, and greater flexibility in microgrid operations, ultimately supporting sustainable and resilient energy systems.

Dennai, M. Y. (2025), The article provides a comprehensive review of advancements in Maximum Power Point Tracking (MPPT) algorithms, specifically within microgrid applications. It highlights the critical role of MPPT in maximizing energy extraction from photovoltaic systems under fluctuating solar irradiance and environmental conditions. Various MPPT techniques are analyzed, including conventional, intelligent, and hybrid methods, with a focus on improving tracking accuracy, response speed, and system stability. The study emphasizes strategies to enhance robustness against unpredictable weather variations and load changes, ensuring reliable and efficient power generation. Overall, it underscores the importance of optimized MPPT algorithms for sustainable microgrid performance.

Kang, X. (2025), This study presents an analytical framework aimed at optimizing the capacity of building microgrid systems while assessing both cost and carbon efficiency. The framework focuses on achieving an optimal balance between energy production and consumption, ensuring that the microgrid operates efficiently and sustainably. By evaluating different generation and storage configurations, the approach identifies the most cost-effective and environmentally friendly solutions for energy management. It highlights the significance of integrating renewable energy sources, such as solar PV, with intelligent control systems to reduce reliance on fossil fuels, minimize carbon emissions, and enhance the overall sustainability of building energy systems.

Hamadneh, T. (2025), The research focuses on optimizing energy management in a hybrid microgrid integrating multiple renewable and conventional sources, including photovoltaic (PV) panels, wind turbines, fuel cells, microturbines, and battery energy storage systems. The study aims to ensure efficient energy utilization, maintain grid stability, and meet load demands throughout the day. A 24-hour operational schedule is considered, accounting for variations in solar irradiance and wind conditions. The EMS optimally coordinates power generation, storage, and distribution between grid-connected and local loads. This approach enhances reliability, reduces dependency on fossil fuels, and improves the overall efficiency of hybrid microgrid systems.

Saleem, M. I. (2024), The proposed Energy Management System (EMS) is designed to optimize the operation of a solar battery microgrid. It effectively manages the charging and discharging cycles of the battery, ensuring longer battery life and reliable energy supply. By intelligently controlling the Distributed Generation (DG) units, the EMS reduces unnecessary operating hours, thereby improving system efficiency and lowering operational costs. Additionally, it mitigates power fluctuations from the photovoltaic (PV) system, maintaining a stable and continuous energy output. Overall, this optimized EMS enhances the performance, reliability, and sustainability of solar battery-based microgrid systems for commercial and residential applications.

Katche, M. L. (2023), This paper presents a comprehensive review of Maximum Power Point Tracking (MPPT) methods used in photovoltaic (PV) systems. The MPPT techniques are classified into four categories: conventional methods, intelligent algorithms, optimization-based approaches, and hybrid strategies. The study evaluates each method in terms of critical performance parameters, including tracking speed, overall energy efficiency, cost-effectiveness, operational stability, and complexity of implementation. The review highlights the advantages and limitations of each approach, providing insights into selecting suitable MPPT techniques for different PV applications. It also emphasizes the importance of balancing efficiency and practical feasibility in real-world systems.

Arunkumar, A. P. (2022), The article explores various strategies and methodologies for achieving effective energy management in microgrid systems. It examines techniques for optimizing power generation, storage, and distribution while addressing the challenges posed by renewable energy variability and load fluctuations. Emphasis is placed on integrating advanced control algorithms, such as model predictive control and intelligent scheduling, to enhance system efficiency. The study also highlights the role of distributed energy resources and energy storage systems in ensuring reliable and stable operation. Finally, it provides insights into future trends and innovations in Energy Management Systems (EMS) to improve performance, sustainability, and resilience of microgrids.

Ahmethodšić, L. (2023), This paper presents a comprehensive review of energy management systems (EMS) in microgrid control, highlighting their crucial role in optimizing energy generation, storage, and consumption. It classifies EMS strategies into conventional, intelligent, and hybrid approaches, analyzing their applications in grid-connected and standalone microgrids. The study discusses key challenges, including variability of renewable sources, load management, and integration of energy storage systems. Furthermore, it explores future research directions, emphasizing the need for advanced control algorithms, real-time monitoring, and predictive strategies to enhance efficiency, reliability, and sustainability, ultimately improving microgrid performance in commercial and residential applications.

B) Literature Summary

Recent studies emphasize the critical role of Energy Management Systems (EMS) in enhancing the performance, reliability, and efficiency of microgrid systems integrating renewable energy sources. Researchers have demonstrated that EMS strategies help balance supply and demand, optimize distributed generation, and reduce energy losses in solar-based microgrids. Battery Energy Storage Systems (BESS) have been identified as essential components for mitigating the intermittency of solar PV generation and ensuring continuous power supply. Advanced Maximum Power Point Tracking (MPPT) techniques have been developed to maximize energy extraction under varying environmental conditions. Hybrid microgrid frameworks integrating PV, storage, and grid connectivity improve operational flexibility and sustainability. Intelligent control approaches, including predictive and optimization-based methods, further enhance load management and system stability. Overall, the literature highlights that integrating PV systems with storage and smart control strategies significantly improves energy efficiency, reliability, and sustainability in commercial building energy systems.

C) Research Gap

Despite significant advancements, several gaps remain in the implementation of solar PV-based microgrids for commercial buildings. Many existing studies focus on standalone renewable integration but lack comprehensive EMS frameworks combining PV generation, battery storage, and intelligent load prioritization. MPPT techniques often perform efficiently under ideal conditions but show reduced effectiveness under partial shading and dynamic weather variations. Limited research addresses real-time load categorization into secured and non-secured loads to ensure uninterrupted power for critical operations. Additionally, the potential for energy sharing among multiple commercial buildings through microgrid networks remains underexplored. IoT-enabled monitoring and real-time decision-making capabilities are also insufficiently integrated into current EMS designs. Furthermore, few simulation-based studies evaluate system performance under both grid-connected and standalone modes, highlighting the need for scalable, intelligent, and reliable energy management solutions for sustainable commercial infrastructure.

4.Research Methodology

A) Criteria for selecting this study:

The selection of a Solar PV-based microgrid system for commercial buildings is driven by the urgent need to address rising energy demand, environmental concerns, and the limitations of conventional power systems. Commercial buildings consume large amounts of electricity for HVAC systems, lighting, elevators, computing infrastructure, and security operations. Dependence on fossil-fuel-based grid power increases operational costs and contributes significantly to carbon emissions. Solar photovoltaic energy offers a clean, abundant, and sustainable alternative, making it an ideal solution for decentralized energy generation. However, the intermittent nature of solar energy necessitates efficient energy storage and intelligent management systems. Microgrid technology enables localized generation, storage, and distribution, ensuring improved reliability and reduced transmission losses. The integration of an Energy Management System (EMS) further enhances system efficiency by optimizing power flow and prioritizing critical loads. This study is selected due to its potential to improve energy reliability, reduce carbon footprint, support sustainable infrastructure, and promote smart energy utilization in modern commercial buildings.

- Rising electricity demand in commercial buildings
- Need to reduce carbon emissions and fossil fuel dependence
- Ab availability and sustainability of solar energy
- Requirement for reliable 24×7 power supply
- Importance of battery storage integration
- Need for intelligent load management and EMS
- Potential for energy efficiency and cost savings
- Support for sustainable and smart building infrastructure

B) Method of analysis:

The proposed Solar PV-based microgrid system is analyzed using simulation-based modeling to evaluate its performance, efficiency, and reliability under varying operating conditions. MATLAB/Simulink is used to design and simulate the photovoltaic system, MPPT controller, battery storage unit, inverter, and Energy Management System. The hill-climbing MPPT algorithm is implemented to ensure maximum power extraction from the PV array under changing irradiance conditions. The EMS monitors load demand, battery state of charge, and PV output to manage energy flow between PV generation, storage, and grid supply. System performance is evaluated under both grid-connected and standalone modes to assess operational flexibility. Load prioritization is tested by categorizing loads into secured and non-secured groups to ensure uninterrupted supply to critical loads. Key performance parameters such as power output, battery charging/discharging behavior, energy efficiency, voltage stability, and reliability are analyzed. The simulation results are used to optimize system parameters and validate the effectiveness of the proposed microgrid system.

- Modeling and simulation using MATLAB/Simulink
- Implementation of hill-climbing MPPT algorithm
- Integration of PV, battery storage, inverter, and EMS
- Analysis under grid-connected and standalone modes

- Monitoring battery state of charge and load demand
- Load prioritization for secured and non-secured loads
- Evaluation of power output and energy efficiency
- Assessment of voltage stability and system reliability
- Optimization of PV size and battery capacity
- Validation of EMS performance through simulation

E) Highlighting trends, advancements, and challenges

Emerging Trends
- Increasing adoption of solar PV microgrids in commercial infrastructures.
- Transition toward decentralized and distributed energy generation systems.
- Growing use of smart buildings with integrated renewable energy solutions.
- Expansion of battery energy storage for continuous power availability.
- Integration of IoT-based monitoring and automation in energy systems.
- Emphasis on energy efficiency and carbon footprint reduction strategies.

Recent Advancements
- Development of high-efficiency PV panels and improved inverter technologies.
- Advanced MPPT algorithms for enhanced power extraction under variable conditions.
- Intelligent Energy Management Systems enabling real-time power optimization.
- Improvements in lithium-ion battery storage performance and lifespan.
- Smart grid integration for seamless grid-connected and islanded operation.
- Simulation and AI-based predictive energy management techniques.

Key Challenges
- Intermittent solar generation due to weather and daylight variability.
- High initial installation cost of PV and battery storage systems.
- Complexity in integrating microgrids with existing distribution networks.
- Limited awareness and adoption in commercial buildings.
- Battery degradation and disposal concerns affecting sustainability.
- Need for advanced control strategies for reliable energy management.

5.Discussion

A) Existing Configuration

The existing power supply configuration for commercial buildings primarily relies on centralized grid electricity generated from conventional fossil-fuel-based power plants [1]. Electrical energy is distributed through utility networks and supplied to buildings to meet demands for lighting, HVAC systems, elevators, and electronic equipment. Backup power is typically provided through diesel generators or basic UPS systems to ensure continuity during grid outages [2]. Although some buildings incorporate small-scale solar installations, their usage is generally limited to water heating or partial lighting loads, resulting in underutilization of renewable energy potential [3]. The absence of integrated energy storage and intelligent energy management systems leads to inefficient power utilization and increased operational costs [4]. Additionally, the centralized grid-dependent structure is vulnerable to power fluctuations, outages, and rising electricity tariffs, making it unsustainable for long-term energy security and environmental sustainability [5].

B) Proposed Configuration work

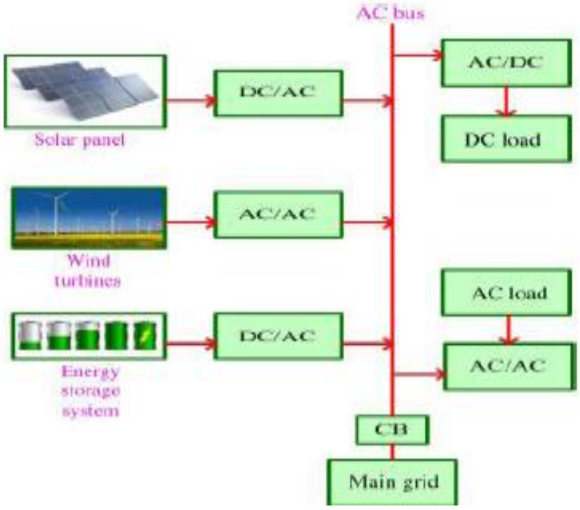

Fig 1: The main concept of a microgrid

The proposed system represents a hybrid microgrid architecture designed to ensure reliable and efficient power supply for commercial buildings. A photovoltaic (PV) generation unit forms the primary energy source, where an advanced Maximum Power Point Tracking (MPPT) algorithm maximizes solar energy extraction under varying irradiance conditions. The PV system is integrated with a Battery Energy Storage System (BESS) connected to the DC bus to store excess energy and supply power during low solar availability.

A UPS unit supports both critical and flexible loads, ensuring uninterrupted power for secured loads during outages or standalone operation. Non-critical loads receive power from PV, battery storage, or the main grid depending on availability. The Energy Management System (EMS) monitors load demand and generation levels, dynamically switching energy sources to maintain efficiency and reliability.

A voltage source inverter with static synchronous compensation enhances power quality by regulating voltage, correcting power factor, and mitigating harmonics. Grid synchronization at the Point of Common Coupling (PCC) ensures stable grid interaction and improved overall system performance.

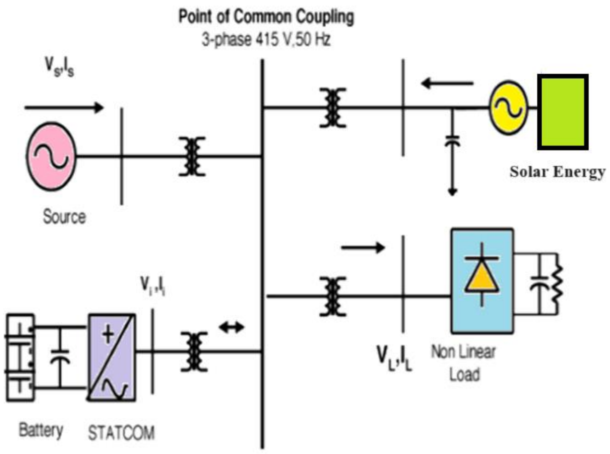

Fig.2.Grid Connected Solar Energy System

In this project, solar photovoltaic (PV) panels are installed on the rooftops of commercial buildings such as schools, colleges, hotels, and supermarkets to generate clean electrical energy. The electricity produced by the PV panels is regulated through a charge controller, which manages power flow and protects the battery from overcharging. A portion of the generated power is supplied to a solar tracking system that continuously aligns the panels with the sun to maximize energy capture. The remaining energy is utilized for building loads and battery charging.

The battery backup system stores surplus energy for use during nighttime or low sunlight conditions, ensuring uninterrupted power supply. The generated DC power is transmitted through DC distribution cables and delivered via a DC Distribution Box (DCDB). For long-distance transmission and voltage regulation, a DC–DC boost converter is used. A protection mechanism allows instant disconnection of the microgrid during faults. The modular microgrid design also supports expansion, enabling multiple buildings to be interconnected for improved energy sharing and reliability.

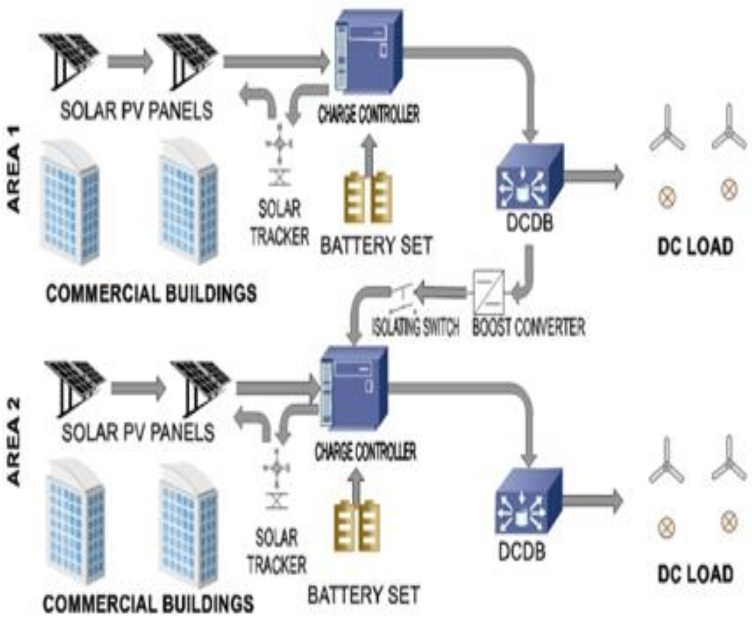

Fig.3.Solar PV based Microgrid for Buildings

Solar power generation can effectively meet the electrical energy demands of commercial buildings by utilizing rooftop photovoltaic (PV) installations. Commercial facilities such as offices, shopping complexes, and educational institutions require substantial electricity for lighting, cooling, and electronic equipment. By installing PV panels, solar energy is converted into electrical power and regulated through charge controllers to ensure safe operation and efficient battery charging. Solar tracking systems can be used to align panels with the sun, maximizing energy capture throughout the day.

When daily energy consumption exceeds solar generation, battery storage systems provide essential backup power to maintain continuous supply. Stored energy supports operations during nighttime, peak demand periods, or cloudy conditions. The generated DC power is distributed through DC distribution boxes (DCDB) to supply DC loads efficiently, reducing conversion losses.

Solar energy is particularly significant among renewable sources because it contributes to other energy cycles such as wind, biomass, and hydropower. Due to widespread solar radiation across the Earth, solar PV systems offer a reliable and sustainable solution for reducing grid dependence and enhancing energy security in commercial buildings.

Table 2: Main Parameters Considered for Study

Parameter	Description	Significance in Study
Total Harmonic Distortion (THD)	Measure of harmonic distortion present in current and voltage waveforms.	Indicates power quality level and effectiveness of harmonic mitigation techniques.
EV Charger Power Rating	Charging capacity (e.g., 3 kW slow charging, 50 kW fast charging).	Determines harmonic magnitude and grid loading impact.
Charging Mode	Different operating modes such as 13A, 32A, or fast DC charging.	Helps evaluate harmonic variation under different operating conditions.
Number of Connected EVs	Total EV chargers operating simultaneously.	Assesses aggregated harmonic impact on the distribution network.
DC-Link Voltage Stability	Voltage level across the inverter DC link.	Ensures stable inverter operation and continuous harmonic compensation.
PV Power Generation	Power produced by the photovoltaic system.	Supports load sharing and enables active filtering during daylight operation.
Solar Irradiance Variation	Changes in sunlight affecting PV output.	Evaluates system performance under dynamic renewable energy conditions.
Reactive Power Compensation	Ability to supply or absorb reactive power.	Improves power factor and enhances grid voltage stability.
Inverter Switching Frequency	Frequency at which inverter switches operate.	Influences harmonic suppression efficiency and system losses.
Grid Voltage Profile	Voltage stability at point of common coupling (PCC).	Determines overall power quality and system reliability.

C) *Analysis of data*

- Solar irradiance data is analyzed to evaluate PV power generation under varying weather and daylight conditions.
- MPPT performance is examined to verify maximum power extraction efficiency from the PV array.
- Battery State of Charge (SOC) variations are monitored to assess charging and discharging cycles.
- Load demand profiles are studied to understand peak consumption periods in commercial buildings.
- Energy flow between PV, battery storage, and grid supply is analyzed for optimal utilization.
- Secured and non-secured load performance is evaluated during grid failure and standalone operation.
- Power quality parameters such as voltage stability and power factor are observed to ensure system reliability.
- System efficiency is calculated by comparing generated power with consumed energy.
- Simulation outputs are analyzed under grid-connected and islanded modes for operational flexibility.
- Energy savings and reduction in grid dependency are assessed to determine sustainability benefits.
- Loss analysis is conducted to evaluate conversion and transmission efficiency.
- Overall system reliability and performance improvements are validated through simulation results.

6. Conclusion

The review highlights the growing importance of solar photovoltaic (PV) based microgrid systems as a sustainable solution for meeting the increasing energy demands of commercial buildings. Integrating renewable energy sources with Energy Management Systems (EMS) and Battery Energy Storage Systems (BESS) significantly enhances energy reliability, efficiency, and sustainability. The literature indicates that advanced EMS strategies play a crucial role in optimizing power flow, balancing supply and demand, and ensuring stable operation under both grid-connected and standalone modes. Maximum Power Point Tracking (MPPT) techniques have demonstrated substantial improvements in solar energy extraction, particularly under varying environmental conditions. Battery storage integration effectively mitigates the intermittent nature of solar energy and ensures uninterrupted power supply for critical loads.

Despite these advancements, challenges remain in real-time load prioritization, intelligent control integration, and large-scale implementation in commercial infrastructures. Future research should focus on IoT-enabled monitoring, AI-based predictive energy management, and cost-effective storage solutions. Overall, PV-based microgrids represent a promising pathway toward reducing carbon emissions, improving energy security, and promoting sustainable power systems for modern commercial buildings.

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