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Design and Simulation of a Renewable Energy-Based Hybrid Microgrid System

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Abstract: The transition to low-carbon and sustainable energy solutions has accelerated the advancement of hybrid microgrids, which integrate multiple renewable sources with energy storage and smart control mechanisms. This study focuses on the modeling and simulation of a hybrid microgrid incorporating solar photovoltaic (PV), wind energy conversion systems (WECS), and battery energy storage systems (BESS) within a unified control framework. The system's performance is analyzed in both grid-connected and islanded modes using MATLAB/Simulink, considering variations in solar irradiance, wind speed, and load fluctuations. To maintain voltage and frequency stability, Maximum Power Point Tracking (MPPT), droop control, and real-time energy management techniques are employed. Simulation results demonstrate the system's ability to provide reliable and high-quality power while mitigating the variability of renewable energy sources. This research supports the development of resilient energy infrastructures, promoting decentralization and carbon-neutral power generation.
Keywords: Renewable Energy,Hybrid Microgrid Solar PV, Wind Energy, Energy Storage, MATLAB/Simulink, Smart Grid, MPPT etc.

I. INTRODUCTION

The global energy sector is undergoing a major transformation as countries strive to reduce the impacts of climate change, enhance energy security, and meet the growing demand for electricity. Traditional centralized power systems, which heavily depend on fossil fuels, are increasingly seen as unsustainable due to their high greenhouse gas emissions, finite fuel resources, and vulnerability to large-scale disruptions. As a result, decentralized energy solutions, particularly microgrids, have gained traction as viable alternatives to conventional grid infrastructure.

Microgrids are localized power networks that integrate various distributed energy resources (DERs), including renewable sources like solar and wind, along with energy storage and intelligent control mechanisms. Among these, hybrid microgrids—combining multiple renewable sources with battery storage—are emerging as a highly efficient and reliable solution. The inherent variability of renewables poses a challenge to grid stability; however, hybrid configurations leverage the complementary generation patterns of different energy sources. For example, solar power is most effective during daylight hours, whereas wind energy production may peak during the evening or in specific seasons. By strategically combining these resources, hybrid microgrids can achieve more consistent and stable power generation.Battery Energy Storage Systems (BESS) play a crucial role in further enhancing the efficiency of hybrid microgrids by providing load balancing, peak demand management, and transient stability support. When integrated with advanced control techniques such as Maximum Power Point Tracking (MPPT), droop control, and dynamic power flow optimization, these systems can ensure steady and high-quality power delivery under varying load and environmental conditions.This study aims to develop a comprehensive simulation model of a hybrid microgrid consisting of solar photovoltaic (PV) panels, wind turbines, and lithium-ion battery storage using MATLAB/Simulink. The objective is to analyze the system's ability to maintain power quality, reliability, and operational stability under dynamic conditions. By offering a detailed simulation framework, this research highlights the role of hybrid microgrids in shaping the future of energy systems, particularly in regions where traditional grid expansion is challenging, such as rural and remote areas or locations prone to natural disasters.

II. LITERATURE REVIEW

Drs. Jayeshkumar Pitroda, Lalakiya Biraj, Naghera Dhiraj, Narodiya Jay, Patel Harsh Proposed Volume 2, Issue 5 of the International Journal of Creative Research on Civil Engineering (IJCRCE). The current society uses electrical energy for free. This energy source is mainly generated by burning fossil fuels. These fats slow down and contribute to pollution. Throughout the daily solar cycle of the year, thereby reducing the dependence on energy-efficient heating and cooling systems. It is clear from evaluating the data that passive solar house design is essential for reducing energy use by using solar energy.

This environmentally friendly design idea makes strategic use of solar heat, highlighting the use of elements like thoughtfully placed windows, walls, and flooring to retain heat from the sun in the winter and release it in the summer. The literature evaluations that follow highlight the many benefits that come with having a solar-powered system.

Deepak Purohit, Goverdhan Singh, Udit Mamodiya, investigated "The technique of using solar panels to capture solar energy is covered in "Review Paper on Solar Energy Systems," which was published in the International Journal for Engineering Research & General Sciences (volume 5, Issue 5, September-October, 2017). The process by which sunlight is transformed into electrical energy by these panels—which are made up of several solar cells—is referred to as solar energy conversion. The solar plant is made up of linked solar panels, each of which has several cells organised according to unique metal lines. By creating a quadrilateral shape, these lines efficiently trap light over a vast surface area. Electrons can be released from the complex metal arrangement and travel along tiny lines to the metal frame. The resultant current passes via the supply cables and into the diode box, which is located behind the panel.

L.G. Meegahapola, Member, IEEE, D. Robinson, A.P. Agalgaonkar, Senior Member, IEEE proposed "The expanding importance of Sustainable Mobility is explored in the article "Solar Energy at Cars: Ideas, Opportunities, & Problems," which was given at the GTAA Meeting on Mulhouse of May 26–27, 2010. The significant influence that automobile systems have on the release of carbon dioxide emissions, global warming, and the urgent need to cut back on the use of fossil fuels are the main causes of this increased attention. Recently, there have been significant efforts made to incorporate solar energy in electric and hybrid cars, prompted by improvements in the efficiency and affordability of photovoltaic panels. Even with these advancements, there is still disagreement about whether it is practical to use solar energy in automobiles. The goal of the article is to explore the potential concepts, possibilities, and difficulties related to solar energy integration in cars while addressing frequently asked issues and concerns. The information offered is based on the writers' own research, specifically in relation to hybrid solar vehicles.

Kumaresh.V, Mridul Malhotra, Ramakrishna N and Saravana Prabu. R reviewed and reviewed in "The paper "Solar MPPT Systems," which was published from Volume 4, Number 3 (2014) under ISSN 2231-1297, examines the growing need for power in a variety of fields. The necessity to capture solar energy and transform it into energy has become more apparent as a way to reduce fuel usage, as electricity is essential to many industries. Cost and efficiency concerns have historically prevented solar cells from being widely used in electrical applications. However, recent developments have significantly increased the effectiveness of solar cells, especially with the use of MPPT (Maximum Power Point Tracking) algorithms. In order to shed light on the revolutionary influence of many MPPT algorithms in the field of solar energy utilisation, the study carefully analyses and explores the applications of each method.

X. Q. Zhai, R. Z. Wang, Y. J. Dai, J. Y. Wu, Y. X. Xu, L. H. Deng develops Design And Experimental Analysis Of Solar-Powered Hybrid Hybrid System In The Ecological Building "2005 International Building Conference, Tokyo, 27-29 September 2005. The importance of environmental building as a new design idea has increased dramatically on a worldwide scale, making it a crucial issue for the construction sector. With the help of natural energy sources like wind and solar electricity, this strategy seeks to attain the goal of significantly lowering dependency on fossil fuels. This paradigm change has made solar systems increasingly important. Modern solar systems, in contrast to their more traditional predecessors, are integrated into building designs rather than existing in the binary as either inactive or working. The concepts of halting and starting become redundant when solar components are seamlessly integrated into contemporary constructions. Notable are the performance parameters of solar collecting systems, which average about 40%. These systems show an average warming capacity of 12 kW when it comes to solar cooling, along with a COP of 0.28. Through the use of redesigned tubes, the natural air intake operating mode further improves efficiency by lowering the air temperature differential between the inlet and output. The typical working mode is reduced by four times as a result of this adjustment, which doubles the natural air velocity. Moreover, under winter conditions, the low-temperature rooms that are outfitted with a solar-powered low-temperature system record temperatures that are 9.3°C and 3°C greater, respectively, below ground and in the air, above their counterparts.

Qianwen Xu, Student Member, IEEE, Jianfang Xiao, Member, IEEE, Peng Wang, Senior Member, IEEE, Xuewei Pan, Member, IEEE, and Changyun Wen, Fellow, IEEE Sakshi Gupta, Neha Sharma proposes " A Decentralized Control Strategy for Autonomous Shared Power Sharing and Reimbursement of Costs in Integrated Energy Conservation Systems ". A power management approach is outlined that utilises integrated energy storage devices to accomplish both state-of-charge (SoC) acquisition and temporary power sharing at the same time. Using a stand-alone SoC recover loop, a unique virtual capacitance droop management approach is presented in this framework to maximise power conservation in an energy storage (ES) system with variable response characteristics.Furthermore, ES is controlled using a typical virtual resistance decrease control technique, which has a sluggish and flexible response. An example of the suggested method is used using a hybrid battery/supercapacitor system (SC).

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Interestingly, to adequately account for the SC and battery, the load capacity is automatically divided into the higher and lower frequency components. This design allows for uninterrupted operation as a power saving without requiring mode switching or operating transitions because the SC's SoC is immediately identified. A thorough design guide is being developed to guarantee smooth cooperation in order to attain the intended short-term capacity and ease the procurement of SoCs. In order to verify the effectiveness of the suggested approach, a number of thorough simulations and assessments have been carried out, with positive outcomes.

Yanzhi Wang, Student Member, IEEE, Xue Lin, Student Member, IEEE, and Massoud Pedram, Companion, IEEE. The idea is to include energy storage and solar (PV) power generation into the Smart Grid, which will effectively reduce the amount of fossil fuels used. This is especially important now that variable energy pricing are in place since customers may use power-control devices and PV-based power generation to optimise their energy demand profiles and lower their electricity costs. During the recurring payment period, the energy price that demand amount are considered, together with the real role of the power price. PV power production and power consumption estimates are used in the household storage control algorithm due to the complexity of the electricity pricing function the energy storage capacity. It deals with a variety of power losses that occur during system operation, such as those caused by the rotating power conversion cycle's breakdown rate and system failure rate. In order to efficiently regulate the charge/discharge of the system of storage with polynomial time complexities at the start of each day, a proximal technique is presented to compute these properties. In order to improve the system even further, at the conclusion of each day during the payment period, a reinforcement learning technique is added to stochastically estimate the remaining energy in the system for storage.

III. SYSTEM CONFIGURATION AND INSTRUMENTATION

The hybrid microgrid developed in this study integrates three primary energy sources: solar photovoltaic (PV) panels, wind turbine generators (WTGs), and a battery energy storage system (BESS). These components are linked via a central AC bus, which facilitates efficient energy exchange between the generation units, connected loads, and the main grid. A dedicated Energy Management System (EMS) oversees real-time operations, ensuring that power distribution remains efficient, stable, and reliable.

The solar PV system consists of multiple solar panels arranged in a series-parallel configuration to generate DC electricity. A DC-DC boost converter regulates the output voltage, maximizing energy efficiency under fluctuating solar irradiance. To integrate with the AC network, a voltage source inverter (VSI) synchronizes the PV output to the AC bus, supplying active power while maintaining voltage stability. The wind energy system features a horizontal-axis wind turbine coupled to a Permanent Magnet Synchronous Generator (PMSG). The electrical output, initially in variable-frequency AC, undergoes rectification followed by inversion to ensure compatibility with the AC grid. Advanced aerodynamic modeling is incorporated to simulate turbine performance under varying wind conditions, including changes in speed and air density.

The battery storage system consists of lithium-ion battery modules, managed through a bidirectional DC-DC converter. This setup allows for controlled charging and discharging, regulated by a state-of-charge (SOC) controller. The BESS not only bridges power gaps during periods of low renewable generation but also contributes to grid stability by mitigating frequency fluctuations and supporting transient load variations. A network of sensors is strategically placed throughout the microgrid for continuous monitoring. Voltage and current sensors track electrical parameters at key junctions, while power meters provide real-time measurements of active and reactive power. The EMS processes this data to optimize energy flow, maintain system balance, and enhance overall operational performance.

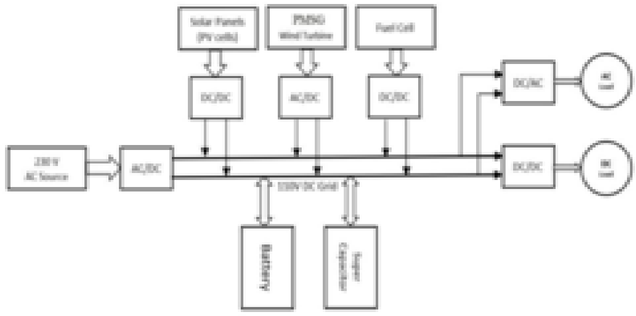

Fig 1. Configuration of DC Microgrid

IV. MODELING AND CONTROL STRATEGIES

The hybrid microgrid was modeled and simulated using the MATLAB/Simulink platform, allowing for a detailed analysis of its dynamic behavior under varying operating conditions. Each subsystem was designed to reflect real-world performance, incorporating nonlinearities, time-dependent variations, and environmental influences. The simulation framework includes representations of power electronic converters, energy generation units, and control strategies to ensure efficient power management.

The solar PV subsystem is based on a single-diode equivalent circuit model, accounting for the effects of irradiance and temperature on energy generation. To maximize power extraction, a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm continuously adjusts the duty cycle of the DC-DC boost converter. This regulated output is then fed into an inverter that utilizes a phase-locked loop (PLL) for synchronization with the AC bus. The inverter operates with pulse-width modulation (PWM) to ensure high-quality waveform generation.

The wind energy system includes a Permanent Magnet Synchronous Generator (PMSG) driven by a horizontal-axis wind turbine. The variable-frequency AC output is rectified and then converted back to synchronized AC. Advanced control mechanisms are implemented to maintain system stability and optimize energy conversion.

Overall, the simulation framework provides an effective means of evaluating microgrid performance under diverse scenarios, ensuring stable and efficient energy distribution.

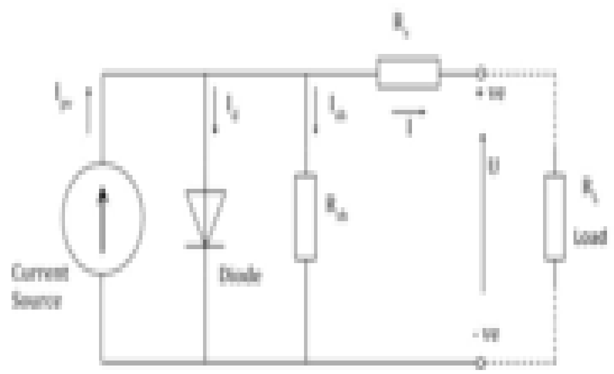

Fig 2. Equivalent Circuit of PV Module

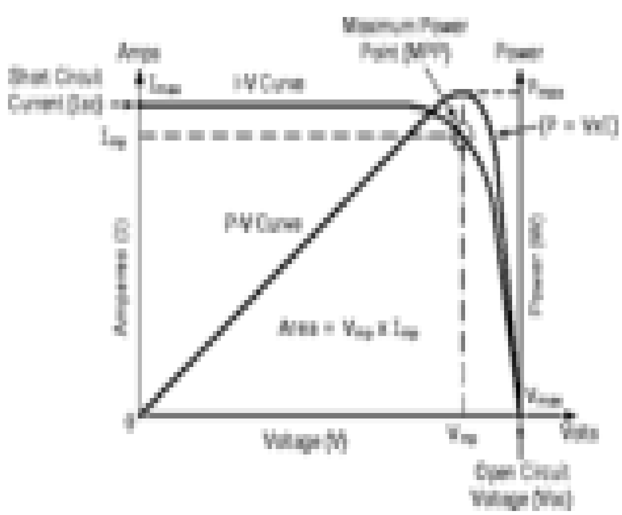

Fig 3. Characteristics Curve of PV Module

The wind turbine model determines mechanical torque based on the power coefficient curve, wind speed, air density, and blade radius. This mechanical torque drives a Permanent Magnet Synchronous Generator (PMSG), which is modeled in the dq0 reference frame to facilitate dynamic analysis. The generated variable-frequency AC is first rectified to DC and then converted back to AC using an inverter for grid compatibility.

A back-to-back converter, consisting of a rectifier and an inverter, is employed to enable independent control of active and reactive power. The rectifier stabilizes the DC link voltage, while the inverter ensures synchronized AC output using a phase-locked loop (PLL). Pulse-width modulation (PWM) is applied to enhance power quality and minimize harmonic distortions.

This simulation approach provides a detailed representation of wind energy conversion, enabling accurate performance analysis under fluctuating wind conditions while ensuring stable and efficient integration with the hybrid microgrid.

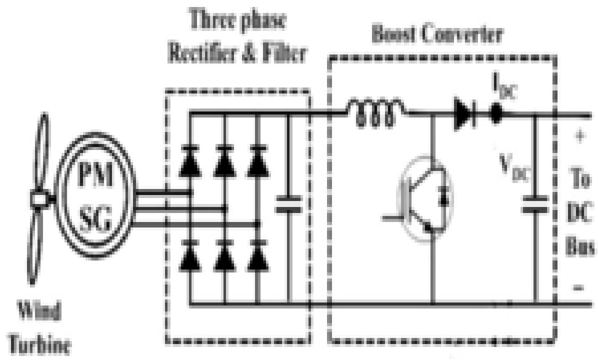

Fig 4. Equivalent Circuit of Wind energy System

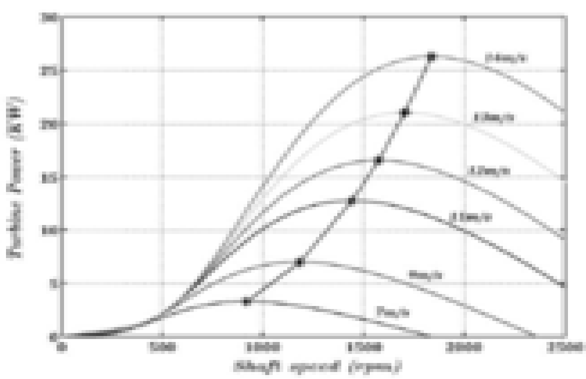

Fig 5. Characteristics Curve of wind Module

The battery storage system is modeled to account for critical parameters such as charge/discharge efficiency, internal resistance, voltage constraints, and aging effects. A lithium-ion battery model is used, with its state of charge (SOC) dynamically tracked to reflect real-time energy availability.

The Energy Management System (EMS) regulates the charging and discharging process based on system demands, ensuring optimal energy utilization and preventing overcharging or deep discharge. A bidirectional DC-DC converter is employed to control power flow, with switching governed by a combination of hysteresis control and PID-based logic. This approach maintains voltage stability while responding efficiently to fluctuations in load and generation.

By incorporating these control mechanisms, the battery system effectively supports load balancing, peak shaving, and transient stability. The model provides a realistic representation of battery performance, allowing for accurate assessment of its role in maintaining the reliability and efficiency of the hybrid microgrid.

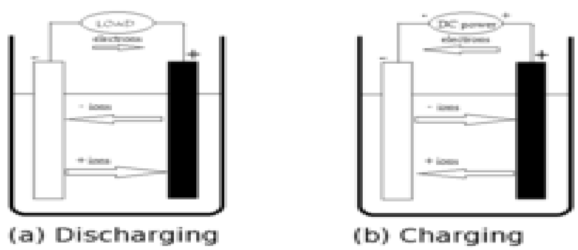

Fig 6. Working of rechargeable batteries

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The supervisory Energy Management System (EMS) oversees the real-time operation of the hybrid microgrid, ensuring efficient power distribution and system stability. It dynamically regulates real and reactive power flow using power-factor correction and load-following strategies to optimize energy utilization. By continuously monitoring generation, storage, and load conditions, the EMS makes intelligent decisions to balance supply and demand.

Advanced control algorithms are embedded within the EMS to handle load prioritization, ensuring critical loads receive uninterrupted power during fluctuations. Additionally, fault detection and handling mechanisms enhance system reliability by mitigating disturbances and maintaining operational stability. Battery protection logic is also incorporated to prevent overcharging, deep discharge, and thermal stress, thereby extending battery life.

With its comprehensive control strategies, the EMS enhances overall system efficiency, minimizes power losses, and ensures seamless coordination between renewable sources and storage. This approach enables a stable and resilient energy supply under dynamic operating conditions.

V. SIMULATION AND RESULTS

To assess the performance of the proposed hybrid microgrid, multiple simulation scenarios were conducted using MATLAB/Simulink. These scenarios were designed to evaluate the system's adaptability, control accuracy, and power quality under varying environmental and load conditions. The analysis focused on the microgrid's ability to maintain stability and efficiency across different operational states.

The simulations covered steady-state conditions to verify power balance and voltage regulation. Transient analysis was performed to examine system response to sudden changes in generation and load, ensuring smooth dynamic behavior. Fault conditions, such as voltage sags and component failures, were also simulated to assess system resilience and fault-handling capabilities.

By analyzing real and reactive power flow, voltage stability, and frequency response, the study provides insights into the effectiveness of the control strategies implemented. These results validate the reliability of the hybrid microgrid in delivering stable and high-quality power under dynamic conditions.

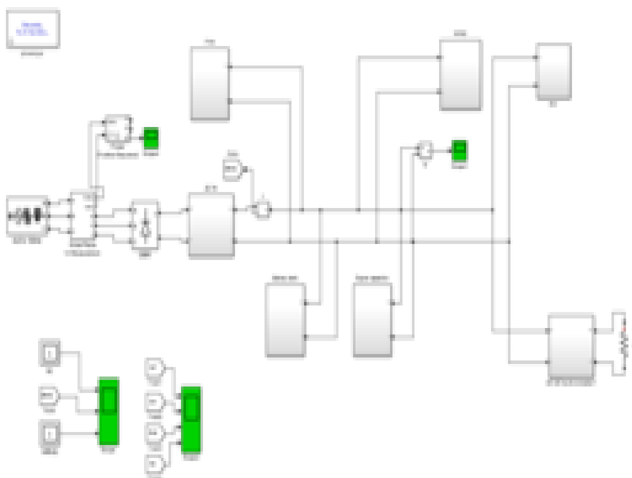

Fig 7. Simulation diagram of proposed system

To evaluate the hybrid microgrid's performance, multiple simulation scenarios were conducted under varying environmental and load conditions.In the first scenario, the system operated under moderate solar irradiance of 700 W/m² and a wind speed of 8 m/s. The load demand was maintained at a steady 7.5 kW. The Energy Management System (EMS) efficiently allocated power between the photovoltaic (PV) and wind turbine generators, ensuring a stable grid voltage of 230 V and frequency of 50 Hz. As power generation closely matched the load demand, the battery energy storage system (BESS) remained idle, maintaining system equilibrium.

In the second scenario, surplus energy generation was tested with peak solar irradiance (1000 W/m²) and high wind speeds (12 m/s), while the load demand was relatively low at 4 kW. The excess power was directed towards charging the BESS, increasing its state of charge (SOC) from 45% to 85%. The EMS actively controlled inverter outputs to prevent overvoltage at the central AC bus. Harmonic distortion remained under 4%, ensuring compliance with IEEE 519 standards for power quality.

A third scenario examined power deficit conditions, where both solar and wind inputs were minimal, and the load demand surged to 10 kW. The BESS responded by discharging at a controlled rate, effectively supplying the load for over 90% of the duration without requiring additional grid support. The SOC of the battery reduced from 80% to 35%, and inverter control maintained voltage deviations within ±2% of nominal values. Grid support was only activated once the battery approached its discharge threshold, ensuring system reliability.

Throughout all scenarios, power quality indicators confirmed stable and efficient energy delivery. The EMS successfully managed real and reactive power flow, maintaining voltage stability and optimizing renewable energy utilization under dynamic operating conditions.

VI. APPLICATIONS

1) Reliable Power Supply – Ensures a stable and uninterrupted power supply by integrating multiple renewable energy sources.
2) Grid Stability Improvement – Enhances grid reliability by using a combination of PV, wind, and fuel cell energy sources.
3) Energy Storage Management – Utilizes batteries and supercapacitors to store excess energy for future use.
4) DC Microgrid Implementation – Provides efficient power distribution to both DC (48V) and AC (110V) loads.
5) Renewable Energy Utilization – Reduces dependency on conventional energy sources by maximizing the use of clean energy.
6) Industrial Power Supply – Suitable for industries requiring stable power with backup energy storage.
7) Remote and Off-Grid Applications – Useful in rural or remote areas where conventional grid access is limited.
8) Smart Grid Integration – Can be incorporated into modern smart grid systems for optimized energy management.
9) Energy Efficiency Enhancement – Improves power efficiency by using individualized converters for controlled energy delivery.

VII. CONCLUSION

This research highlights the effectiveness of a hybrid microgrid integrating solar PV, wind turbines, and battery energy storage in delivering stable and reliable power. The simulation results confirm the system’s ability to efficiently manage fluctuations in supply and demand while maintaining high power quality and minimizing losses. Through advanced control strategies such as Maximum Power Point Tracking (MPPT), power-factor correction, and dynamic State of Charge (SOC) monitoring, the microgrid ensures optimized energy utilization and enhanced stability.

The Energy Management System (EMS) plays a crucial role in regulating real and reactive power flow, balancing load variations, and protecting battery health. By dynamically adjusting power distribution and responding to real-time environmental changes, the system operates efficiently under diverse conditions.

Hybrid microgrids hold significant potential for deployment in off-grid and semi-urban areas, as well as in regions prone to power disruptions. Their ability to integrate renewable energy sources makes them a viable solution for reducing reliance on fossil fuels and supporting the transition to sustainable energy infrastructures. The findings of this study reinforce the importance of hybrid microgrids in modern power systems, contributing to energy security and environmental sustainability.

VIII. FUTURE SCOPE

The proposed hybrid microgrid system offers numerous avenues for future enhancement. First, real-time hardware implementation using embedded controllers like dSPACE, OPAL-RT, or NI myRIO can provide deeper insights into system behavior. Second, integration of predictive analytics through machine learning models can enhance load forecasting, renewable generation prediction, and fault detection. Additionally, bidirectional charging and vehicle-to-grid (V2G) technology can be incorporated through electric vehicles as mobile energy storage units.

Other promising directions include cybersecurity frameworks for EMS protection, blockchain-based energy trading among microgrids, and advanced optimization techniques (e.g., PSO, GA) for techno-economic sizing. Expansion into peer-to-peer energy sharing models and the use of hybrid AC/DC bus structures can also significantly improve system efficiency and applicability in smart grid ecosystems.

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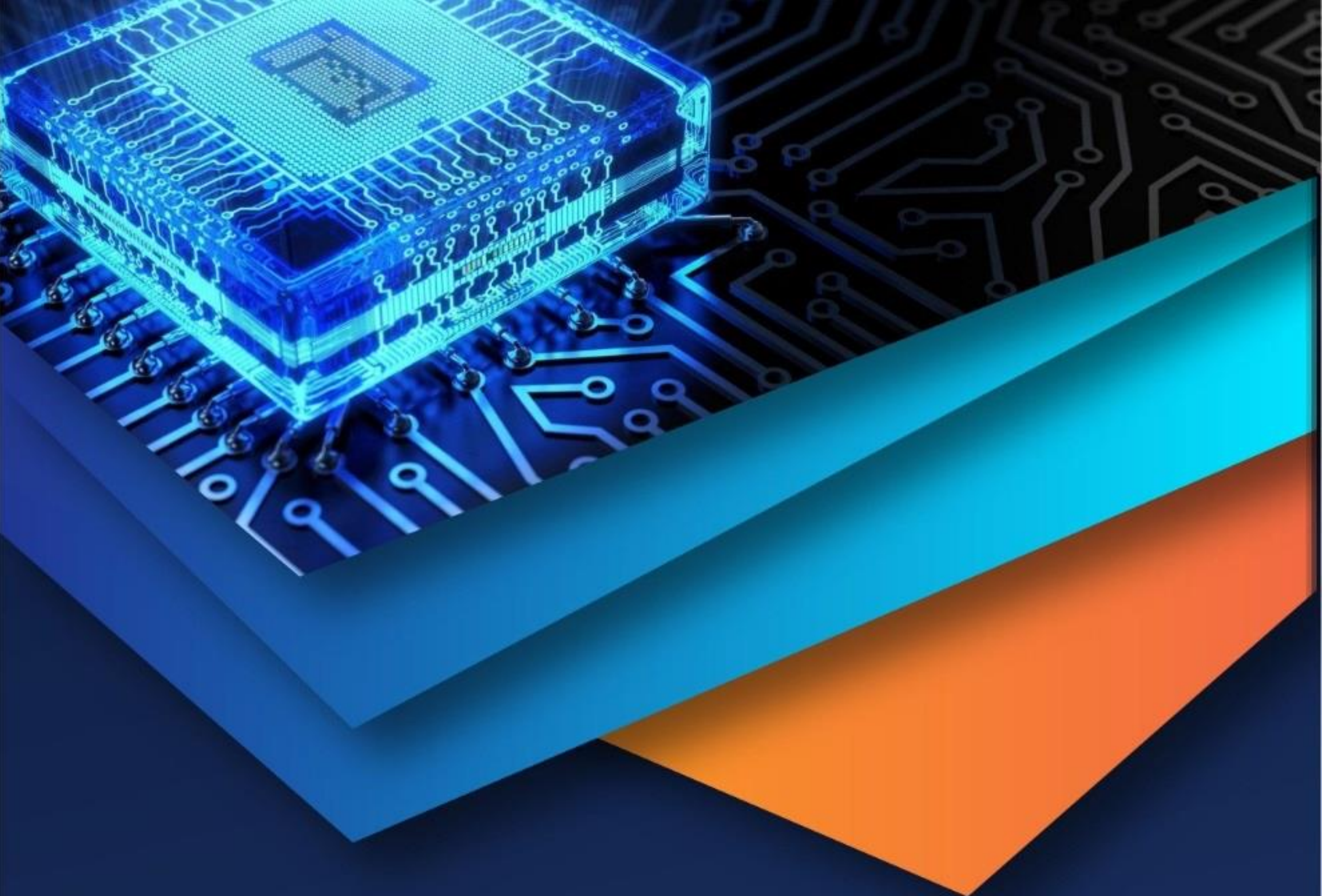

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