International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Review on Advanced Energy Management System for Renewable Based Microgrids Using Optimization and Intelligent Control Techniques

[1]Ankita Pandey, [2]Prof. Monika Patel
[1]M.Tech Scholar Electrical Engineering Department Rewa Engineering College, Rewa MP, 486001
[2]Assistant Professor Electrical Engineering Department Rewa Engineering College, Rewa MP, 486001

ABSTRACT
The increasing penetration of renewable energy sources in microgrids introduces challenges related to intermittency, uncertainty, and dynamic load variations. This paper reviews advanced Energy Management System (EMS) strategies that integrate optimization techniques and intelligent control methods for efficient microgrid operation. Classical and metaheuristic optimization approaches are analyzed for energy scheduling, while artificial intelligence-based techniques such as neural networks and reinforcement learning are examined for real-time adaptive control. The study highlights the importance of hybrid EMS frameworks to address multi-objective problems, including cost, reliability, and emission reduction. Key challenges such as scalability, computational complexity, and system security are also discussed. The review concludes that intelligent, optimization-driven EMS solutions are essential for achieving reliable and sustainable operation of renewable-based microgrids.
Keywords: AI-driven EMS, microgrids, renewable energy integration, load balancing, machine learning

I. INTRODUCTION
One of the most efficient ways to produce energy is through fossil fuels, which include coal, oil, and natural gas. Recent scientific research demonstrates that these energy sources have detrimental effects on human health and the environment in addition to their economic effects [1,2,3]. Along with these effects, because of different reasons such as increasing energy demand, increasing energy prices, energy source dependency, etc., scientists are investigating alternate energy resources. Renewable energy resources and distributed generation have historically been used to try to meet the needs of reducing the negative effects of electrical energy production on the environment, meeting the ever-increasing demand for electrical energy, and improving the quality, reliability, and stability of power systems [4,5,6].
Increasing the capacity of electrical networks and extending transmission lines to feed farther-off electrical loads raise the costs of producing electrical energy as well as transmission–distribution losses due to the growing electricity demand [7]. Distributed generation which mostly employs renewable resources like solar and wind power is a good opportunity to solve these problems. Microgrids, which are small-size power grids, are also proposed for the same purpose. A microgrid can employ conventional and renewable distributed energy resources. Microgrids can supply energy to local-regional loads or the main power grid with these resources. Therefore, nearby loads can receive electrical energy from energy sources that are

dispersed throughout a given area. They can also run in island mode (off-grid) or grid-connected (on-grid) mode. From these angles, microgrids provide many advantages for the future of power grids [8]. Microgrids containing renewable energy sources are used to reduce the annual electricity bill, energy purchased from the grid, and greenhouse gas emissions in the conventional power system. Microgrids can be used to increase the sustainability of electricity supply and minimize poverty in developing countries [9].

The large inertia moments of large power generators are crucial in suppressing oscillations in voltage and frequency that occur in traditional power systems. Compared to conventional generators, distributed generation units in microgrids are more unstable due to system oscillations in voltage and frequency because they are connected to the grid through power electronic converters [10]. To guarantee that microgrids run consistently, effectively, and in compliance with standards, a control system must be developed. Numerous problems, including voltage-frequency regulation, proper load sharing, synchronization with the main grid, control of the power flow between the microgrid and the main grid, and operating cost optimization, should be solved by this control system [11]. For the distributed energy resources that microgrids use as power sources to cooperate effectively, energy management is crucial.

Efficient, safe, and intelligent use of distributed energy resources among microgrid components is important for power quality and supply–demand balance in the system. This can be achieved by using energy management systems in microgrids. Numerous approaches, including multi-agent systems, model predictive control, artificial intelligence techniques, meta-heuristic-based methods, stochastic and robust programming-based methods, and classical method-based approaches, are used in microgrid energy management systems [12].

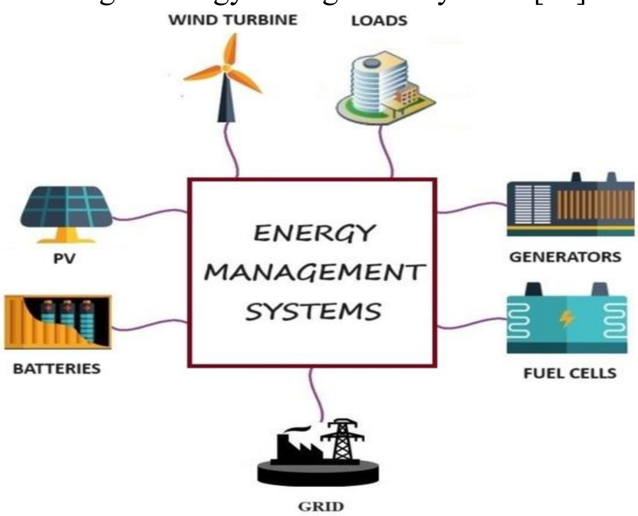

Fig 1. Energy management in microgrid units.

II. RESEARCH MOTIVATION

Microgrids have emerged as a promising solution for enhancing energy resilience and sustainability, particularly with the growing integration of renewable energy sources such as solar and wind. These localized energy systems are designed to operate autonomously or in connection with the main grid, allowing for improved energy efficiency and reliability.

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However, the variability and intermittency of renewable energy resources pose significant challenges in maintaining a balanced energy supply and demand within microgrids. To address these issues, advanced Energy Management Systems (EMS) are crucial for optimizing power distribution, ensuring grid stability, and maximizing the utilization of renewable energy. This paper explores the development and implementation of an AI-driven Energy Management System for microgrids, designed to enhance the efficiency and reliability of energy distribution. By leveraging machine learning algorithms, the proposed system can predict energy demand and optimize the allocation of power in real-time, taking into account both renewable energy generation and fluctuating energy needs. This approach aims to overcome the limitations of traditional EMS methods, which often struggle to adapt to the dynamic nature of renewable energy sources and the varying demands within microgrids.

III. PROBLEM STATEMENT

The integration of renewable energy sources into microgrids introduces challenges related to the unpredictability and intermittency of power generation. Traditional Energy Management Systems (EMS) lack the ability to dynamically respond to these fluctuations in real-time, leading to inefficient energy distribution, grid instability, and underutilization of renewable resources. As microgrids increasingly incorporate renewable energy, there is an urgent need for more advanced EMS capable of optimizing power distribution and maintaining stability.

The increasing integration of renewable energy sources such as solar and wind into microgrids has introduced significant challenges in effective energy management due to their intermittent and uncertain nature. This variability leads to frequent mismatches between power generation and demand, making reliable and efficient operation difficult. Conventional Energy Management Systems (EMS), which primarily rely on deterministic and rule-based approaches, are not capable of handling such dynamic and nonlinear conditions. Furthermore, traditional optimization techniques such as linear programming and mixed-integer methods suffer from high computational complexity and are not suitable for real-time energy scheduling in large-scale microgrid environments.

Another major issue lies in the lack of adaptive and intelligent control mechanisms within existing EMS frameworks. These systems fail to respond effectively to rapid changes in load demand, renewable generation, and system disturbances. The integration of energy storage systems adds further complexity, as optimal charging and discharging strategies are required to maintain system stability and extend battery life. Additionally, the increasing penetration of electric vehicles introduces stochastic and high-power demand patterns, which, if not properly managed, can lead to peak load issues and grid instability. Demand-side management also remains underutilized due to the absence of real-time pricing strategies and limited consumer participation.

Moreover, microgrids operate under multiple conflicting objectives, such as minimizing operational cost, reducing emissions, and maintaining reliability, which makes the optimization problem highly complex and multi-dimensional. Existing EMS solutions often struggle to achieve a global optimum under such constraints. Scalability is another concern, as modern microgrids consist of multiple distributed energy resources, loads, and control units, increasing system complexity and computational burden. Challenges also arise in ensuring seamless operation between grid-connected and islanded modes, where stability and power quality must be maintained during transitions. In addition, the lack of IoT-enabled real-time monitoring, cybersecurity measures, and standardized EMS architectures further limits the effectiveness and practical deployment of current systems. These issues collectively highlight the need for advanced EMS frameworks that integrate intelligent control techniques with efficient optimization methods to ensure reliable, scalable, and real-time operation of renewable-based microgrids.

IV. LITERATURE REVIEW

Omer Faruk Ozcan et al.[1] The stochastic nature of renewable energy sources and load demand poses significant challenges to maintaining voltage and frequency stability in islanded microgrids. To address these challenges, this paper proposes an adaptive voltage–frequency control framework based on a Genetic–Gray Wolf Optimized interval Type-II Sugeno fuzzy logic controller. The proposed system integrates a hydrogen fuel cell into a hybrid microgrid that considers multi-source uncertainties on both the generation and demand sides. In this configuration, short-term fluctuations in renewable energy generation are compensated by the battery energy storage system, while the fuel cell provides long-term power support, ensuring system sustainability and stability. Renewable and load variations are modeled using probabilistic distributions, and a roulette wheel mechanism dynamically selects one of 20 stochastic scenarios to represent various uncertainty conditions. The proposed GGWO–Type II fuzzy controller is evaluated under four operating scenarios, including manual and optimized demand response programs. The simulation results demonstrate that it outperforms conventional P/F and Q/V droop and Type-I fuzzy controllers, achieving superior voltage–frequency regulation and faster transient recovery under uncertainty.

Renjin et al.[2] A microgrid is an advanced infrastructure that offers increased sustainability, dependability, and local energy autonomy by incorporating renewable and hybrid energy sources into the utility system. However, uncertainties arising from the intermittent nature of renewable sources, fluctuating loads, and dynamic electricity market prices present significant challenges for efficient operation. Traditional heuristic-based energy management systems (EMS) rely on forecasted data but often lack precision and adaptability under real-world variability. To address these limitations, this research proposes a novel Fuzzy Logic Controller-based EMS (FLC-EMS) for optimizing microgrid performance. Unlike rigid rule-based or computationally intensive linear programming (LP) methods, the proposed FLC-EMS combines intelligent decision-making with responsiveness and cost-effectiveness. Simulation results demonstrate that the FLC-EMS outperforms both heuristic and LP-based EMS strategies. Specifically, it achieves cost savings of approximately 8.1% on clear days and 16.6% on cloudy days compared to heuristic methods, while offering additional savings of 1.6–5.5% over LP-based optimization. Furthermore, FLC-EMS reduces grid energy usage and effectively manages state-of-charge (SoC) variations, resulting in enhanced utilization of renewable resources and lower reliance on grid power. The integrated microgrid model and EMS framework developed in this study serve as a robust platform for smart grid applications, offering scalability, real-time adaptability, and improved consumer economics. This work positions the FLC-EMS as a promising candidate for advanced microgrid control, paving the way for resilient and intelligent next-generation power systems.

Yan Jiang et al.[3] This study develops a green-finance–oriented optimization framework for microgrid operation by integrating thermal units, renewable energy, and CHP systems using the Integrated Swarming Strategy Algorithm (ISSA). Four planning scenarios—probabilistic and randomized, with and without CHP—are evaluated under variable market prices and environmental constraints. ISSA achieved a 95.28 % success rate in reducing operational costs and consistently generated higher profits when aligned with carbon pricing and renewable subsidy mechanisms. The results show that combining ISSA optimization with green finance incentives significantly enhances microgrid profitability and sustainability. Future work will focus on climate-adaptive heating loads and carbon–neutral planning.

C. Mahiba et al.[4] Renewable-integrated Microgrids experience continuous operational variability and therefore require adaptive and intelligent control mechanisms capable of responding to dynamic conditions. This paper presents a Federated Edge Reinforcement Optimization (FERO) framework that combines the advantages of Edge AI, Deep Reinforcement Learning (DRL), and blockchain-IoT coordination for robust cyber-physical control. The FERO design does not employ the traditional AI model or federated DRL concepts rather usages multiple federated agents of DRL at the edge for proactive fault prediction, enhancement of voltage stability, and dynamic power dispatch at the same time under the changing renewable penetration. The individual semi-autonomous agents use LSTM to encode reinforcement policies, enabling localized, independent decision-making for real-time control. A federated optimizer aggregates policy updates without revealing sensitive operational data, thus preserving privacy while maintaining collaborative learning. In parallel, a blockchain layer with delegated proof-of-authority consensus is used for controlling all transactions and inter-microgrid state updates.

Muhammad Irfan et al.[5] The growing reliance on fossil fuels for energy and transportation accelerates environmental degradation and depletes natural resources. Integrating Renewable Energy Sources (RESs) and Electric Vehicles (EVs) into microgrids offers a sustainable alternative; however, effective energy management remains challenging due to the intermittent nature of renewable generation and variable load demands. Some studies encounter challenges in effectively managing generation variability, load fluctuations, and uncertainties using advanced algorithms. This paper presents a novel hybrid controller—Model Predictive Control-Tuned Imitation Learning with Long Short-Term Memory (MPC-TIL-LSTM)—designed to optimize energy distribution, storage operations, and vehicle-to-grid interactions. The proposed controller predicts optimal energy allocation, mitigates fluctuations from intermittent RESs using storage systems, and ensures efficient load scheduling to maintain microgrid stability. Performance is evaluated under diverse scenarios involving RESs integration, EV charging/discharging, and varying load conditions.

Peter Anuoluwapo Gbadega et al.[6] Integrating renewable energy sources (RESs) into multi-area microgrids introduces significant challenges to maintaining system stability and frequency regulation due to the inherent intermittency and variability of RESs. This study proposes an innovative approach to enhance the multi-area automatic generation control (AGC) of renewable energy-based microgrids by employing a robust Fractional Order Proportional-Integral-Derivative (FOPID) controller optimized using the Cheetah Optimizer Algorithm (COA).

Zhuoting Cheng et al.[7] The increasing penetration of renewable energy sources and bidirectionally controlled electric vehicles into microgrids introduces significant uncertainty in generation output, electricity market prices, and user behavior. These uncertainties pose substantial challenges to achieving reliable, economical, and flexible microgrid scheduling. This paper proposes a robust multi-time-scale scheduling framework that integrates renewable energy interpretation with advanced optimization techniques. A distributionally robust optimization model is developed for day-ahead planning, capturing renewable energy variability and electric vehicle dynamics through an ambiguity set constructed from historical data. The non-convex scheduling problem is solved using an adaptive Harris Hawks Optimization algorithm, which enhances convergence stability and search diversity.

Yuqing Yang et al.[8] The growing demand for renewable energy has promoted the development of hybrid microgrids integrating fuel cells(FCs) and photovoltaic(PV) systems. However, the inherent variability of these sources, coupled with dynamic load conditions in standalone microgrids, often causes power imbalance, inefficient energy allocation, and DC bus voltage fluctuations, thereby threatening system stability and resilience.

Rampelli Manojkumar et al.[9] The increasing integration of renewable energy sources (RESs) and battery energy storage systems (BESSs) into hybrid AC/DC microgrids offers opportunities for cost reduction and flexibility but poses challenges in control. This paper proposes a PSO-tuned rule-based energy management system (EMS) that coordinates photovoltaic (PV) generation, BESS, and the utility grid under dynamic pricing. The framework integrates price-based demand response (DR), adaptive battery operation rules, and real-time forecasts to minimize energy consumption cost (ECC). Compared with Genetic Algorithms, PSO achieves faster convergence and higher computational efficiency.

Tariq Limouni et al.[10] With the depletion of fossil fuels, the integration of renewable energy sources as distributed energy resources has become mandatory. However, the uncertainty and intermittent nature of these sources introduce significant challenges to their integration into microgrids. Effective control systems are essential for ensuring smooth integration, managing energy storage systems, and maintaining microgrid safety. In this study, a review of recent control methods applied in microgrid management was conducted with a focus on AI, optimization, and predictive techniques.

Nilesh Chothani et al.[11] The planning and operation of microgrids rely on efficient energy management, especially where the generation of renewable sources is high, intermittent, and unpredictable. The intermittent characteristics of solar energy and wind velocity pose a significant challenge in ensuring economic viability, voltage stability, and safe operation. In order to solve these problems, this paper suggests a Levy Flight Particle Swarm Optimization (LFPSO)-based techno-economic optimization model of optimal integration of wind, solar, micro-turbine distributed generators, and energy storage systems within a grid-connected micro-grid.

Ouassima El Qouarti et al.[12] Tertiary hierarchical control of AC/DC Hybrid Microgrids (HMGs) or Energy Management System (EMS) is a widely discussed literature topic. It aims to provide well-performing systems grid interaction according to internal and external constraints, such as electricity market prices and utility grid requirements as macro-decisive vectors, and the MG local demand and generation as micro-decisive factors. In this paper, our objective is to perform the tertiary control on a grid-tied AC/DC HMG that incorporates renewable energies, distributed generation using Proton Exchange Membrane Fuel Cell (PEMFC), along with batteries and electrolysis, in order to minimize the operational cost of the MG, maximize the use of renewable energies, and reduce the emissions based on variable wind/solar irradiation profiles and loads curves that reflect a real industrial consumption behavior.

Tao Liu et al.[13] Microgrid systems integrating heterogeneous energy flows face underexplored challenges in real-time electro-thermal synergy under intermittent renewable input—a gap this study addresses via a dynamically coupled multi-domain optimization framework. To bridge the theoretical gap in coordinated energy dispatch across thermal-electric domains, this paper formulates a DBO-based hybrid microgrid model where the optimizer's phase-based behavioral logic is intrinsically coupled with dynamic thermodynamic constraints. First, the PV/T system leverages its combined heat and power capabilities to meet thermal loads. Then, thermoelectric conversion is realized by integrating an ORC with an air-source heat pump, while energy storage systems—batteries and thermal tanks—recover and utilize waste heat, ensuring electro-thermal balance.

Khadija Azakaf et al.[14] The huge emerging of intermittent renewable energy production systems (RES) in the grids creates instability in the whole system, thereby the role of the integration of different types of energy storage systems (ESS), hence, relaying on one single storage technology is not sufficient to cover this issue. In this context, Hybrid Energy Storage Systems (HESS) were integrated to enhance the stability and resilience of microgrids (MGs). The current paper presents a holistic review of existing ESS technologies, the different possible combination of HESS while integration into MGs, with emphasis on their role in improving frequency stability, voltage regulation, and ensuring seamless transitions between grid-connected and islanded modes.

Aykut Fatih Güven et al.[15] The rapid proliferation of renewable energy sources (RES) and electric vehicles (EVs) has introduced significant challenges in the optimal design and energy management of modern microgrids. This study presents a novel hybrid metaheuristic, the Salp Swarm–Kepler Optimization Algorithm (SSAKOA), which synergistically combines the global exploration capability of the Salp Swarm Algorithm with the orbital-based exploitation efficiency of the Kepler Optimization Algorithm. The proposed algorithm is first rigorously evaluated on a suite of 23 standard benchmark functions to validate its convergence behavior, robustness, and solution quality relative to established metaheuristics. Subsequently, SSAKOA is applied to a grid-connected hybrid renewable energy system comprising photovoltaic panels, wind turbines, battery storage, hydrogen subsystems (electrolyzers, hydrogen tanks, and PEM fuel cells), and bidirectional EV charging capabilities. The microgrid model incorporates realistic meteorological, demand, and tariff data over an annual cycle to simulate real-world conditions.

V. CONCLUSION

This review highlights that the evolution of renewable-based microgrids has significantly increased the complexity of energy management due to the intermittent nature of distributed energy resources, dynamic load patterns, and the integration of energy storage systems and electric vehicles. Conventional Energy Management Systems are no longer sufficient to handle these challenges efficiently, particularly in real-time and multi-objective operational environments. The analysis of existing literature indicates that classical optimization techniques, while effective for simplified problems, face limitations in scalability, computational efficiency, and adaptability when applied to modern microgrids.

The review further demonstrates that intelligent control techniques such as artificial neural networks, fuzzy logic, and reinforcement learning offer promising capabilities for handling uncertainty, nonlinear behavior, and real-time decision-making. Similarly, metaheuristic optimization approaches provide flexible and robust solutions for complex multi-objective problems, including cost minimization, emission reduction, and reliability enhancement. However, no single technique is found to be universally optimal, which emphasizes the growing importance of hybrid approaches that combine optimization algorithms with intelligent control strategies.

In addition, emerging technologies such as IoT-enabled monitoring, smart metering, and decentralized energy trading frameworks are playing a crucial role in enhancing the functionality and responsiveness of advanced EMS architectures. Despite these advancements, several challenges remain, including high computational requirements, cybersecurity risks, lack of standardization, and difficulties in real-time implementation.

Overall, the study concludes that future research should focus on the development of integrated, scalable, and intelligent EMS frameworks that leverage hybrid optimization techniques and AI-based control methods. Such systems should be capable of real-time operation, adaptive learning, and secure communication to ensure reliable, efficient, and sustainable energy management in next-generation renewable-based microgrids.

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