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Advanced strategy for energy management and voltage stability in microgrid-a review

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ABSTRACT

Microgrids (MGs) have emerged as transformative solution for improving energy resilience, stability, and sustainability in modern power systems. By incorporating distributed energy resources (DERs), renewable energy sources (RES), and energy storage systems (ESS), microgrids can supply reliable and stable power to local loads while also supporting the main grid during disturbances. Despite their potential, the efficient operation of MGs depends heavily on well-designed energy management and control systems (EMCS). A key challenge lies in addressing inherent variability of RES such as solar and wind, which introduces uncertainty in generation, as well as the dynamic and unpredictable nature of consumer loads. These factors make strong, adaptive, and intelligent energy management strategies crucial for ensuring both voltage stability and reliable operation. This paper presents review of advanced strategies developed for energy management and voltage stability in microgrids. It explores state-of-the-art optimization techniques, intelligent control methods, and emerging management frameworks that aim to balance generation, storage, and load demand efficiently. The study critically analyzes current methodologies, highlights their limitations, and identifies crucial research gaps in literature. By synthesizing recent developments, the paper provides insights in to innovative approaches that can enhance system reliability, optimize resource utilization, and ensure stable microgrid operation under uncertain conditions.

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1. INTRODUCTION

Burning fossil fuels poses both economic and environmental hazards, the electric power industry has been concentrating on increasing the quantity of electricity generated from renewable energy sources (RESs). RES-based microgrids are gaining popularity, and distributed producers are being employed more frequently in power system generation [1]. Renewable energy is a substantial and abundant energy source in nature. It is becoming increasingly popular since it is more environmentally friendly and emits less carbon than other energy sources. Further to having low negative environmental impact, these green energy sources help save energy and lessen industry's reliance on fossil fuels [2]. A microgrid power supply system that makes it possible to give remote communities access to electricity. These microgrids are distributed energy systems or low voltage networks that provide heat and power to a designated area using a generator load [3]. One option for integrating renewable energy resources (RER) to distribution grids is to use microgrids (MGs), which are made up of loads, distributed generation (DG) units, and energy storage systems (ESS) [4].

The research community has shown a strong interest in MG systems due to their numerous advantages, which include enhanced efficiency, improved power quality, increased security reliability, and numerous environmental benefits [5]. Distributed generation (DG) or local RES might help to overcome the limitations of the traditional grid by boosting output, including generated heat, while minimizing transmission losses [6]. As a result, energy management system control infrastructure and ESSs are essential to power systems and microgrids [7]. The primary purpose of this study is to provide a comprehensive and up-to-date review of the literature on distributed ESSs, as well as their decentralized leadership and management. The foundation of this thorough examination is decentralized control strategies [8]. For example, in several studies, concurrent power sharing is disregarded and only voltage control is taken into account. On the other hand, it’s critical that multiple dispersed generators and energy storage systems share power appropriately. Additionally, energy storage devices (ESDs) have different energy and power densities [9]. Using machine learning (ML) based methods to predict the output of distributed energy resources (DERs) can optimize the functioning of MGs and improve their dependability and efficiency. Unlike previous ways, this can be accomplished by employing techniques like as energy storage devices to compensate for changes in DER output, as well as real-time production and consumption scheduling [10].

A subset of a branch of artificial intelligence (AI) called DRL has become well known for its ability to solve difficult control and decision making problems in a variety of fields [11]. DRL combines the ideas of RL with deep neural networks (DNNs) to enable RL agents to learn the best course of action by interacting with their surroundings [12]. Chen *et al*. [13] have presented a framework for modeling a double deep Q-network (DDQN) and assessing scheduling options that balance communication costs and voltage stability. Zarma *et al*. [14] suggested employing optimal machine learning methodologies to create energy demand forecasting models for hybrid microgrid systems. Sahoo *et al*. [15] created a scaled conjugate-based artificial neural network (SC-ANN) in the MATLAB/Simulink architecture to increase the PQ indices of fuel cell, PV, DVR, as well as energy storage (battery) microgrid systems.

2. METHOD

The search process is implemented to clarify basic concepts relevant to the purpose of the review. Using scientific indexing, standard journal articles from databases like IEEE, Elsevier, and Springer were searched using keywords. An 85 to 90 papers research articles from renowned journals like Elsevier, IEEE, and Springer. A survey of recent studies on energy management and voltage stability published between 2021 and 2025 is also examined. Numerous long-term approach types have been fully evaluated. This paper presents extensive research on energy management, protection, and stability challenges in microgrids. Motivated by these advancements, the main aim of the work is to enhance the voltage profile of a solar photovoltaic (PV)-based grid-connected system while ensuring maximum power extraction from the PV array. To achieve maximum power point tracking (MPPT) under varying environmental conditions, thinking of establishing pufferfish optimization-based quantum neural network (PF-QNN).

Additionally, to mitigate voltage distortion and sudden load variation effects in the grid-connected inverter, an improved coati-optimized adaptive neuro-fuzzy inference system (ANFIS) controller can be used. Now we will discuss about energy management strategies in microgrid energy management allows for the implementation of scenarios like storing excess power in energy storage devices in the event that the system's power requirements are less than the power provided by RES. If the power required exceeds the power provided by renewable energy sources, energy storage devices can be used to supply the difference [16]. Integrate and regulate energy flow across numerous units to ensure dependable, cost-effective operation and demand-supply balance [17]. Figure 1 illustrates the block diagram for MG energy management [18].

2.1. Renewable energy integration

An essential interface for connecting RES, utility grid, end consumers, and even the power electronics converter. The power electronics converters tasks include supplying energy to local customers and/or transferring variable amounts of renewable energy with a fixed frequency and constant voltage amplitude into the utility grid. As a result, power electronics face a variety of intricate needs [19].

The proposed methodology aims to optimize the energy consumption of the microgrid by utilizing batteries and RES [20]. In renewable energy source integration solar microgrid integration and wind powered microgrid integration plays a major role. Because energy production is intermittent, innovations in energy storage technology are required to store additional power in high-demand periods and discharge it during less productive times [21]. RES like hydro, geothermal, solar, wind, as well as biomass, can significantly impact EMS [22]. Figure 2 signifies structure of power electronics system and grid connected RES [23]. Table 1 illustrates the related works based on renewable energy integration.

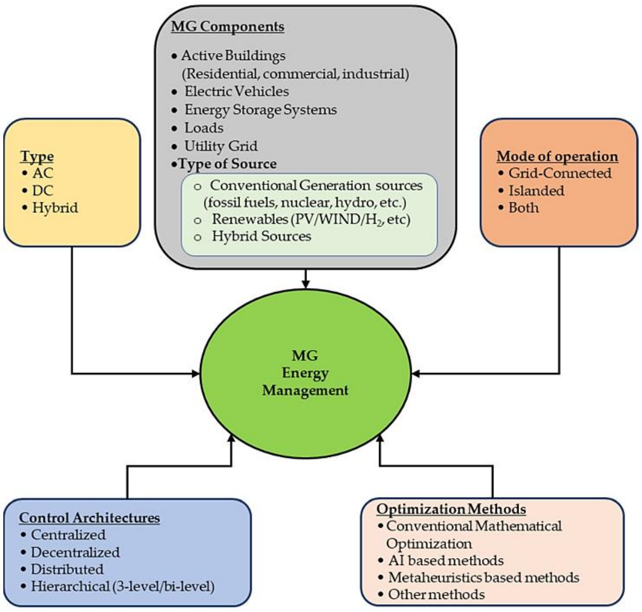

Figure 1. Block diagram for MG energy management

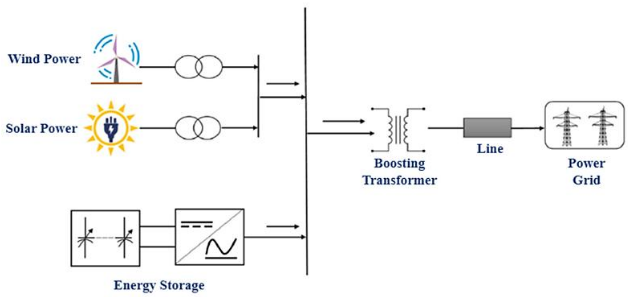

Figure 2. Structure of power electronics system and grid connected RES

Table 1. Related works based on renewable energy integration

Author name	Focused area	Techniques	Input sources	Energy storage system	Addressed challenges	Key outcomes
Thirunavukkarasu *et al.* [24]	Distribution generation in DC microgrids	Multi-agent, meta-heuristics, mixed integer programming	Solar PV, wind	Storage system	Dispatch, decentralized EMS, forecasting demand	Need for demand prediction and collaborative scheduling
Sarda *et al.* [25]	Optimization in microgrid energy management	Optimization technique and heuristic	Solar PV	Battery	ESS discharge/ charge control	Simulation vs cloudy days optimization
Talebi and Aly [26]	Energy management in solar based microgrid	Hybrid optimization FA-PSO	Solar PV, tidal, wind	BESS	Tidal energy integration, battery degradation	Realistic modelling, better performance than GA, PSO, ACO
Kamal *et al.* [27]	Hybrid microgrid with battery degradation	PSO, GA, differential evolution	Solar wind diesel	Battery	Sizing, sensitivity analysis, economic viability	Cost effective foe rural electrification
Hai *et al.* [28]	Planning for rural area techno-economic microgrid	MMRFO	Solar PV	Storage system	PV uncertainty, seasonal variability	MMRFO outperforms conventional methods, cost effective operation

2.2. Storage system management

For MGs to operate steadily and dependably, energy storage is essential. Energy storage materials unique physical properties allow for particular electrical patterns, which need to be accurately modeled to allow for the safe and efficient use of ESSs [29]. Table 2 represents the related works based on storage system management. Based on their structure and material composition, ESS can be divided into:
- Mechanical ESS
- Electrochemical ESS-flow batteries and secondary batteries
- Thermal ESS
- Chemical ESS-fuel cells
- Electrical ESS-superconducting magnetic and supercapacitors

Table 2. Related works based on storage system management

Author name	Focused area	Technique	Performance evaluated	Overshoot	Input sources	Energy storage system	Key contribution
Ramu *et al.* [30]	Standalone DC microgrid using PV	ANN	Settling time, load balancing, SoC maintenance, voltage profile improvement, overshoot	18% (PV increase), 21% (PV decrease)	Solar PV	Battery, super capacitor	Improves voltage profile and load balancing under variable conditions
Singh *et al.* [31]	DC microgrid control with ESS	Combined cuckoo search and neural network	SoC management, DC bus voltage regulation, voltage overshoot, settling time	Improved compared to conventional methods	Solar PV	Battery, super capacitor	Improves system reliability and dynamic response in real-time environments

2.3. Stability issues in microgrids

This section highlights the various operational features of MGs and DGs and the threats to the stability of power system. The stability problems have three primary causes:
- Reduced system inertia, which causes frequency and angular instability.
- Reduced power supply leads to reduced voltage stability.
- Power sharing ratio modification causes lower frequency oscillations. Stability and electrical service can be improved by decentralizing supplies and maintaining an optimum supply ratio [32].

A facility microgrid and a microgrid based on a single corporate entity are often connected to the host utility. Consequently, a facility-based microgrid keeps operating in an intentional or unintended island. Additionally, industrial or institutional microgrids can benefit greatly from facility based microgrids [33]. Table 3 represents related works based on stability issues in microgrids.

Table 3. Related works based on stability issues in microgrids

Author name	Focused area	Challenges addressed	Key outcome	Types of stability	Causes of instability	Control technique	Load used
Mehta and Basak [34]	Stability analysis of MG	Power imbalance, fault induced instability, load uncertainty	Review in microgrid for stability issues	Transient voltage, small signal	DER losses, islanding, load shedding faults, uncertain load	Adaptive controllers	Load shedding events, general MG loads
Ali *et al.* [35]	Frequency stability using robust virtual inertial control	PLL-induced frequency error, high penetration	Improving frequency stability under contingencies, robust control approach	frequency	PLL-induced fluctuations, RES penetration, lack of inertia	CDM with CCSA	Hybrid MG loads, customer loads, EVs
Xu *et al.* [36]	Control and fault handling in DC shipboard MG	Pulsed load effects, protection, and reconfiguration	Protection in DC shipboard MGs	Transient DC voltage	High bandwidth converter, grounding issues in ships, pulsed loads, negative impedance	Operation mode switching via EMS	Pulsed loads, constant power load, Shipboard loads

2.4. Advanced techniques for voltage stability enhancement in microgrids

Categories of techniques for analyzing voltage stability, including as dynamic and static analysis. Static analysis methods use microgrids static operational parameters to examine voltage stability and identify important variables impacting the stability [37]. Table 4 shows the related works based on voltage stability enhancement in MG.

Table 4. Related works based on voltage stability enhancement in MG

Author name	Technique	Controller	Key contribution	Load type	Voltage issue
Paredes *et al*. [38]	FACT devices	Reactive power compensation	Improves dynamic voltage recovery in MG, DSTATCOM outperforms SVC	DER based MG, IM loads	Dynamic voltage stability
Abbass *et al*. [39]	ANN with ensemble models	-	Lowest MSE, MAE, improved voltage forecast reliability, prediction accuracy	IEEE 4-bus grid model	Nodal stability and voltage prediction
Senapati *et al*. [40]	FA-PSO	FO-PID, TSFIS ANFIS controllers	Voltage with reduced topological constraints	Solar, wind RES, DC MG with EV chargers	Voltage and small signal instability
Tabassum *et al*. [41]	ANFIS	Intelligent voltage control	Voltage stability, sustainable grid operation, improved harmonic filtering	Solar PV and wind integrated microgrid	Voltage fluctuation and harmonic distortion

2.5. Reactive power control

The reference frame in [42] illustrates active and reactive power regulation using PI controllers. It highlights the control strategy applied for managing both types of power. Table 5 shows the related works based on reactive power control.

Table 5. Related works based on reactive power control

Author name	Method	Reactive power issue addressed	Key contribution	System type
Kumar *et al*. [43]	-	Transient/dynamic instability, steady state voltage issues	Suggestions for power management	Power grids
Andrade *et al*. [44]	PI controllers	Frequency and voltage regulation at PCC	VSC via demonstrated active and reactive power flow control	High power solar and wind islanded MG
Wagle *et al*. [45]	Differential evaluation	In PV fluctuations fast voltage regulation occurred	Minimized power loss without full network modelling, faster optimal reactive power control	PV integrated distribution networks
Gao *et al*. [46]	GA	Voltage regulation and power smoothing	Power smoothing validated through simulations, real-time voltage control	BESS connected to microgrid

2.6. Integrated energy management and voltage stability approaches

Malik *et al*. [47] addressed the topic of voltage instability in wind-integrated generators, including its sources, impacts, solutions, and implications for code requirements to ensure network safety. To enable wind integration into power networks, appropriate mitigation strategies must be developed after a thorough knowledge of the fundamental problems associated with voltage instability, highlighting it negatively affects power systems dependability and performance. Saleem *et al*. [48] created a novel EMS for grid-connected MGs to increase MG energy efficiency, prevent BESS deterioration, and ensure that the PCC voltage remains within defined ranges. The recommended EMS uses a finite horizon MPC architecture to seamlessly coordinate BESS activities such as charging, discharging, and reactive power supplies. Emrani-Rahaghi *et al*. [49] suggested a voltage control-oriented EMS as an alternative to more standard techniques such as on-load tap changers (OLTC) and DGR output power limitation

The combined regulation of the electric and thermal supply/demand sides strengthens the suggested strategy in terms of cost savings and power constraint satisfaction. Another addition is to use sensitivity matrix data to calculate and regulate voltage accurately and fast. Zhang *et al*. [50] proposed exploiting latent temporal dependencies to apply DL to STVS evaluation of power systems. Due to the lack of valid quantitative criteria, the class labels of STVS instances are determined using a semi-supervised clustering approach. Then, by learning the time dependencies from the dynamics of the post disturbance system, an LSTM-based assessment model is built. Table 6 represents the survey based on voltage stability and energy management.

Table 6. Survey based on voltage stability and energy management

Author name	Techniques	Voltage stability approach	Focused areas	Energy management feature	Application context	Key contribution
Malik *et al.* [47]	-	-	Wind integrated systems	-	Wind based power systems	Grid codes for stability
Saleem *et al.* [48]	Finite horizon MPC	Maintains PCC voltage under solar variability and load	Grid connected MGs with solar and battery	Reactive power from BESS optimizes cost and SoC	Solar PV, Battery	Ensure voltage constraints and reduce battery degradation
Emrani-Rahaghi *et al.* [49]	-	Manages over/under voltage in networked MGs	Networked multi-energy MG	Electrical and thermal load management	Controllable loads in residential MG	Voltage constraint with minimal cost
Zhang *et al.* [50]	LSTM	Short-term voltage stability	Power systems under disturbances	EMS decision making and supports post disturbance	IEEE 39 bus system	Improves real-time stability

3. DECENTRALIZED AND CENTRALIZED INTEGRATED CONTROL ARCHITECTURES

It goes without saying that when systems expand and develop, centralized control is not always an appropriate solution or even feasible. The efficiency of a control system declines as the amount of data (sensors) and operators rises. Consequently, unavoidably shift towards decentralized control in the modern world. However, MGs are dispersed and decentralized in nature. As a result, it appears that MG will benefit from decentralized control techniques [51]. Table 7 demonstrates the related works based on decentralized and centralized integrated control [52]-[56]. Centralized structure, decentralized structure, and distributed structure are clearly represented in [57].

3.1. Optimization and control techniques

Making model of the power system, which incorporates information like line data, load needs, and generator constraints is the first step of the process. The EMS objective function is then defined, long with then limitations imposed on various operational parameters like voltage magnitudes and angles, and the MGs component limits, with the active as well as reactive power limits of the generators. Setting time parameters for the various algorithms completes this stage [58]. Figure 3 illustrates the classification of energy management optimization methods. MGs energy management optimization methods can be divided into four main groups [24].

- Fuzzy logic-based EMS
- Metaheuristics-based EMS
- Neural network-based EMS
- AI-based EMS

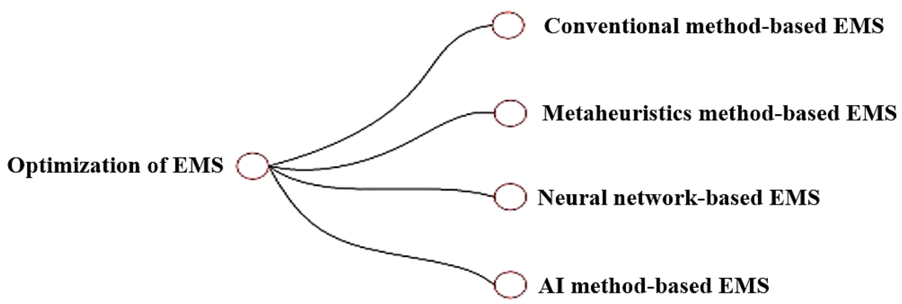

Figure 3. Classification of energy management optimization methods

Table 7. Related works based on decentralized and centralized integrated control

Authors name	Focused area	Centralized/Decentralized	Control approach	System involved	Strategies	Validation method
Habibullah and Kim [52]	Constant voltage regulation combined with adaptive droop control for DCMG	Decentralized	Primary and secondary control with adaptive droop	UG, DG, ESS, EV	Voltage regulation and power sharing, SOC and price aware adaptive droop	Experimental test/simulation
Bhattar and Chaudhari [53]	Centralized energy management scheme for PV-BESS based DCMG	Centralized	Centralized with hierarchical structure	PV, BESS, AC, grid	Peak/off peak multiobjective management, linear programming for PV-BESS	MATLAB/Simulink
Boglou *et al*. [54]	Multi-agent system for EV charging in islanded MG with cost-effective operation	Decentralized	Decentralized using a multi-agent system and fuzzy logic	EV, LV, MG	Reduction of peak load of 17%, load variance reduction of 29%, cost savings of 8.8%	Comparative simulation
Nabatirad *et al*. [55]	Decentralized BESS load sharing with accurate power control in islanded DC MGs.	Decentralized	Modified droop with SOC awareness and superimposed signal	DG, BESS	AC frequency signal for load state to control BESS operation mode, SOC based droop tuning	PLECS simulation
Zhang *et al*. [56]	Decentralized multi-agent DRL for energy internet with MG clusters	Decentralized	MPC	DERs, ERs, microgrids	MPC for upper-layer energy routing and price based dispatching	Performance comparison is based on simulation

Choudhury and Sahoo [59] have suggested numerous beneficial plans and techniques to enhance electricity quality as a result of customer satisfaction. Power quality concerns have been highlighted through the use of filters, controllers, FACTS, optimization techniques, and ML tools with modern and advanced control methods have been emphasized. Mohamed *et al*. [60] have suggested to maximize the performance of PV the study presents an enhanced energy management system that minimizes environmental effect, increases solar energy usage, and decreases diesel consumption based on artificial protozoa optimizer.

Abdelghany *et al*. [61] have presented the HESS primary contribution is the inclusion of several hydrogen storage tanks that usually concentrates on a single tank. In addition to ensuring that reference demands are tracked and most importantly, that the fluctuations of RES are smoothed out, the proposed control method also considers the physical limitations, degrading characteristics, and economic and operational expenses of the HESS. Karthikeyan *et al*. [62] have suggested the artificial bee colony (ABC) algorithm and DL optimization approaches are applied creatively to improve the voltage control and regulation in smart microgrids that are connected to electric vehicles (EVs). The novel technique that optimizes voltage source converter (VSC) using deep learning neural network is suggested.

3.2. Voltage stability enhancement techniques in microgrids

Reactive power imbalance is the root cause of unstable voltage, which is a local phenomenon. The two primary causes of voltage instability are rapid changes in loads or load flow capacity, like a transmission line tripping. Because microgrids' relatively low voltage levels, compensated loads, as well as current-limited inverter performance put the network at danger of voltage instability and collapse, maintaining a steady voltage is a critical component of microgrid function and management [63]. Microgrid's voltage stability issue might arise for a number of causes. The P~V as well as Q~V type curves are utilized to illustrate this occurrence in the microgrid. The P-V curve indicates the maximum load capacity, whereas the Q-V curve indicates the required reactive power near the load to obtain the requisite voltage [33].

Stanchev *et al*. [64] reported the voltage stability in smart microgrids for two different scenarios. A linear low voltage p-type microgrid with loads connected at different nodes is given. The conductor type and cross-section of the power line under study are described. Simulation studies were performed to determine the limitations of grid voltage stability while connecting solar plants to a fixed power source. An investigation of the system's ideal operating mode is conducted, along with commentary on the simulation results. Iqbal *et al*. [65] have suggested to effectively reduce voltage sag and swell in grid-connected microgrids. The fuzzy technique system and ESRF approach form the foundation of the EDVR's control strategy.

3.3. Optimization techniques for energy scheduling and dispatch

Optimization is the process of identifying the best possible solution. There are three types of optimization strategies for optimal power dispatch as represented in Figure 4. Convex optimization problems are solved using the traditional approach, whereas non-convex and practical ELD issues are solved using the nonconventional approach. Additionally, hybrid procedures are employed to enhance the performance of each non-conventional method when solving systems containing more than two of them [66].

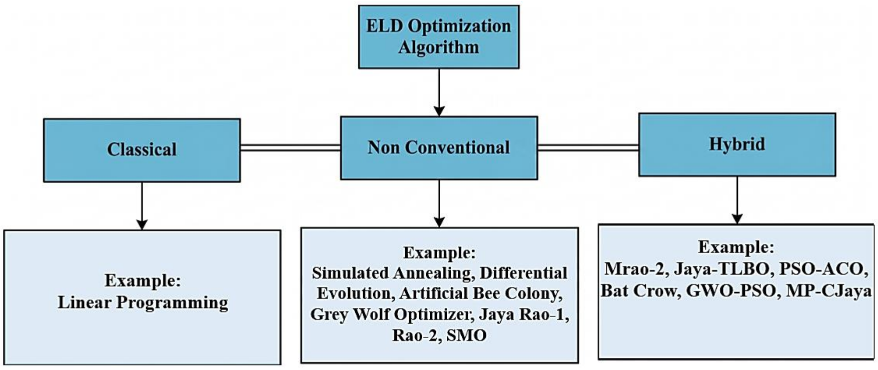

Figure 4. Optimization types

According to Abttan *et al*. [67], both equal and unequal specifications must be met at the lowest possible cost of fuel and carbon pollution. The BA and ALOA are two new metaheuristic techniques that are presented in this study. Sharma *et al*. [68] proposed a modified particle swarm optimization (PSO)-based multi-objective optimization approach for virtual power plant (VPP) schedule in distribution system activities including peak shaving, energy cost elimination, and reliability improvement. The state electrical utility case study, which includes a 90-bus industrial feeder with grid-integrated PVs as distributed energy resources is utilized to assess the viability of the VPP.

According to Liu *et al*. [69], the initial step is day-ahead economic dispatch, with the ultimate goal of system power distribution. The day ahead economic dispatching model's optimization goals are to reduce carbon emissions while increasing energy efficiency and economic benefits. The immediate optimal planning concept is solved utilizing the YALMIP toolkit, while the first stage day advance optimal planning is addressed using the non-dominated sorting genetic algorithm-11 (NSGA-11). Pramila *et al*. [70] have suggested to reduce the operational costs for electrical power suppliers. This study investigates MGs by integrating the newest loads and distributed generators. This research employs sophisticated algorithms such as SMO, the firefly method, as well as a hybrid technique combining the two. Based on the social behavior of spider monkeys, SMO strikes a balance between exploitation and exploration in order to get the best outcomes.

Raju *et al*. [71] proposed a three-level stochastic architecture to improve grid-dependent microgrid efficiency in terms of load capability, reliable voltage, and optimum planning. The newly created Harris Hawk optimizer, inspired by nature, has been included into level three to save expenses and enhance microgrid load capacity. According to Jasim *et al*. [72], the MGs' financial and ecological measures are considered the key objective functions in the suggested optimal DSM-based energy management plan. To optimize MG efficiency in the context of REEs with randomized natural behavior, both single objective PSO (SOPSO) and multi-objective PSO (MOPSO) were considered. The complexity and non-linearity of the suggested problem led to the adoption of a PSO algorithm.

3.4. Integration of renewable energy sources and storage

Rashid [73] suggested the use of energy storage technology, renewable resources, and advanced control systems to improve power system stability. To improve the dependability, predictability, and sustainability of power systems, modern control techniques are strategically integrated with energy storage deployment and renewable energy utilization. A remarkable stability rate of 23.6% is attained by carefully applying the Lyapunov function as well as the reciprocally convex technique in the stability analysis, which concentrates on input-to-state stability. Elkhidir *et al*. [74] have developed to reduce the grid breakdowns, an efficient method for preventing power outages by managing the power network's source voltage is developed. A renewable integrated bus system is used in a case study for small signal stability investigations with optimal size and ESS distribution to lower the output power fluctuation of renewable energy sources.

3.5. Demand-side management strategies

Utility operators have shown an increased interest in the DSM structure in their multiple efforts to reduce net energy usage by utilizing meter technology at the end user level. When DSM-based programs enter the power markets, the firm becomes more profitable and efficient. The primary goal of load management is to reduce peak demand and manage spot pricing volatility [75]. Power management to satisfy energy demand, the microgrid alters the power generation of its local resources, such as generators and energy storage devices, using load monitoring. It also draws power from the main grid [76]. Demand side management is the planning, implementation, and monitoring of distribution network utility activities with the goal of influencing consumer energy consumption in ways that would result in the desired changes to the load shape [77]. DSM has four main strategies: DR, spinning reserve, ToU, and EE. Load shifting is the process of using filling and clipping techniques to transfer the demands for loads from peak to off-peak hours. This approach uses storage devices and the ToU with a fixed level of overall energy consumption [78]. The requirement for security, reliability, and maximized profit has driven research into DSM study themes. The following describes the driving cause for the increased interest in the use of DSM approaches:

- Balance energy availability and resources to meet demand without adding new sources to the system.
- Provide an interactive load management market where customers actively contribute to reducing energy expenditures [79].

Mbungu *et al*. [80] suggested an effective load management control system to address the financial load shifting issue. The control scheme is built on the DG system and a standalone MG, as well as two biomass generation systems, an ESS, and RER (wind and photovoltaic). During the load shedding operation, the best control plan has been implemented to minimize the DG's operating costs, maximize the energy from RERs, and ultimately boost the MG's profit. The under frequency load shedding (ULFS) scheme is developed to optimize the MG-based multi-objective. Alam *et al*. [81] have presented a distribution solution to the DC microgrid control problems. However, the battery only meets the nominal power consumption. The DG power control algorithm ensures that the battery SoC remains within lower and higher limitations.

Razmi and Lu [82] have presented the DG sources for MG applications. These difficulties are described in the categories of power sharing and hierarchical control techniques. Consequently, from a thorough and simple MPC based techniques are examined for various modern and control levels and power sharing schemes. The potential of MPC techniques to manage inverters in order to increase grid reliability a characteristic that could not be accomplished. Dey *et al*. [83] created a demand response (DR) strategy that maximizes the benefits of energy retailers; in this case, microgrid customers are the primary goal. DR models take into account the distinct behaviors of various consumers during both peak and valley phases, considering their utility and elasticity. To determine a new intelligent algorithm is put into place to reduce a microgrid systems overall cost.

Ramadan *et al*. [84] recommended an energy management for a home microgrid that incorporates a PV plant and battery storage device. To strengthen the microgrid's independence from the traditional electrical grid, develop an effective load management system. PSO with ANN helps to pick appliances for DSM load disaggregation. PSO is used to optimize the ANN algorithm that is used in the load detection task. Kumar *et al*. [85] proposed a tri-level optimization methodology for optimal scheduling of autonomous and grid-connected microgrids in order to reduce power losses and boost load capacity. Because the network's voltage profile varies with loading level, the flexible loads shaping-based DSM approach is employed to investigate its effect on microgrid load capabilities.

Sun *et al*. [86] have presented an approach based on particle swarms is suggested for computational efficiency. Significant cost savings are shown by validating the suggested approach and model in various scenarios, highlighting the inventiveness and viability of the combined microgrid and demand side management approach. According to the study, involvement in load response programs significantly lowers peak load. Moazzen and Hossain [87] stated that the higher layer employs a cooperative technique to improve the cluster's overall operational efficiency, whereas the suggested approach generates the optimal day-ahead operation rules. A mixed integer quadratic programming (MIQP) optimization, which includes linear terms in the issue's constraints, provides a precise description of the energy management problem.

4. RESULTS AND DISCUSSION

Conventional PI and PID controllers have been widely used for voltage regulation and inverter control in PV-based microgrid systems due to their simple structure and ease of implementation. However, reported results in the literature indicate that these controllers suffer from fixed gain settings and limited adaptability, leading to poor performance under dynamic irradiance and sudden load variations. As a consequence, voltage regulation is only moderate, and the total harmonic distortion (THD) levels are typically high, often exceeding 3–5%. Fuzzy logic controllers have been introduced to improve system adaptability through rule-based decision-making. While these controllers provide better voltage regulation and moderate improvement in THD performance compared to PI/PID controllers, their effectiveness is strongly dependent on the quality of the predefined rule base. Moreover, the absence of learning capability limits their ability to adapt to changing operating conditions, resulting in THD values generally in the range of 2–4%. ANN-based controllers further enhance control performance by incorporating learning capabilities. ANN-based methods demonstrate improved voltage regulation and MPPT performance; however, they often experience slow convergence and are susceptible to local minima during training. Additionally, retraining is frequently required when system conditions change, leading to THD values typically ranging between 1.5% and 3%. ANFIS controllers combine the advantages of neural networks and fuzzy logic, resulting in better nonlinear mapping and adaptive control capability. Studies employing ANFIS optimized using conventional techniques such as genetic algorithms (GA) or PSO report improved voltage regulation and reduced harmonic distortion, generally achieving THD levels around 1–2%. Nevertheless, these optimization techniques often suffer from premature convergence and inefficient exploration, which limits overall performance improvement. Recent research has also explored DRL-based control strategies, mainly focusing on energy management and scheduling at the system level. Although these methods demonstrate improved voltage stability and operational efficiency, they are computationally intensive and are not specifically designed for real-time inverter control or direct harmonic mitigation, leaving power quality improvement as a secondary objective.

In contrast, the proposed control framework integrates a pufferfish optimization algorithm (PFOA)–based quantum neural network for maximum power point tracking and a coati optimization algorithm (COA)–optimized ANFIS controller for inverter control. This coordinated optimization approach ensures fast convergence, robust voltage regulation, and effective harmonic suppression under dynamic operating conditions. Simulation results confirm that the proposed method achieves significantly lower THD values of 0.52% for voltage and 0.70% for current, outperforming conventional, intelligent, and DRL-based approaches reported in the literature. These results validate the effectiveness of advanced nature-inspired optimization combined with adaptive intelligent control in enhancing power quality, system efficiency, and grid compatibility in PV-based microgrid systems.

5. CONCLUSION

This report presents a comprehensive analysis of existing technologies targeted at enhancing energy management and voltage stability in microgrids. The need of advanced, adaptive, and intelligent control frameworks has the integration of RES, ESS, and dynamic loads such as EVs. This study has examined a wide range of solutions addressing the complex between power flow, voltage regulation, and system reliability from conventional droop based methods to modern data-driven decentralized control schemes. DRL, linear programming, and mixed integer programming are optimization approaches that considerably improve demand side management across both islanded and grid connected operating modes, as well as energy scheduling and reactive power control. The need for robust coordination among distributed components in the presence of high uncertainty, the integration of multi-agent systems with real-time adaptability, and the development of unified frameworks that combine energy management and voltage stability improvement.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

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