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TOPICAL REVIEW

A Review of Microgrid Energy Management and Control Strategies

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ABSTRACT Several issues have been reported with the expansion of the electric power grid and the increasing use of intermittent power sources, such as the need for expensive transmission lines and the issue of cascading blackouts, which can adversely affect critical infrastructures. Microgrids (MG) have been widely accepted as a viable solution to improve grid reliability and resiliency, ensuring continuous power supply to loads. However, to ensure the effective operation of the Distributed Energy Resources (DER), Microgrids must have Energy Management and Control Systems (EMCS). Therefore, considerable research has been conducted to achieve smooth profiles in grid parameters during operation at optimum running cost. This paper aims to provide a review of EMCS techniques that have evolved in recent years. Firstly, the fundamentals of microgrids are discussed for a general overview of the field. Then, a critical literature review is undertaken for the various methods applied for EM optimization in microgrid applications. Multiple factors have been explored in the objective functions throughout this review, including MG daily operational costs, energy storage degradation, revenue through trading with the grid or other parties, and Greenhouse Gas (GHG) emissions. Control systems have been reviewed by categorizing them based on the different applications in MGs for stable operation. This paper also focuses on IEEE standards related to MG operation and control to facilitate other researchers to build upon a standardized set of rules and to enhance the interoperability of the diverse EMCS techniques.

INDEX TERMS Distributed energy resources, energy management systems, energy storage systems, hydrogen, metaheuristic algorithms, microgrid optimization, overview, renewable energy resources, smart grids, standards.

I. INTRODUCTION

A. BACKGROUND

In the past few decades, many significant blackouts in electric power networks were reported around the globe, costing the respective economies millions of dollars worth of losses [1], [2], [3], [4]. In the United States alone, millions of people are affected every year, resulting in the loss of billions of dollars in revenue [3]. The causes of power system faults range from single-location faults resulting from transmission line failure and power plant technical faults to wide-area faults caused by bad weather conditions or natural disasters, as can be observed in Figure 1 and Figure 2. The main concern of these events is that critical loads such as hospitals, airports, and the continuous process industry are affected, in many cases, for long durations of 5-10 hours, and sometimes even more. Moreover, grid restoration takes a considerable amount of time for widespread blackouts. At times, even healthy

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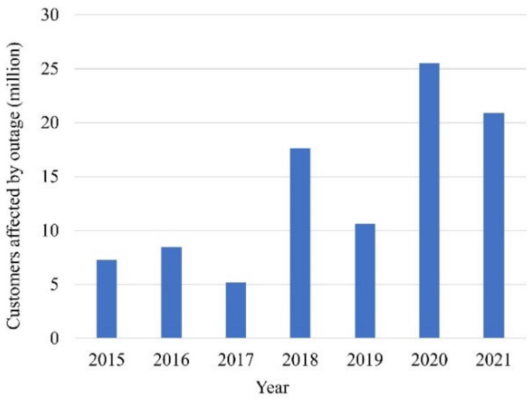

FIGURE 1. Causes of blackouts in the united states [14].

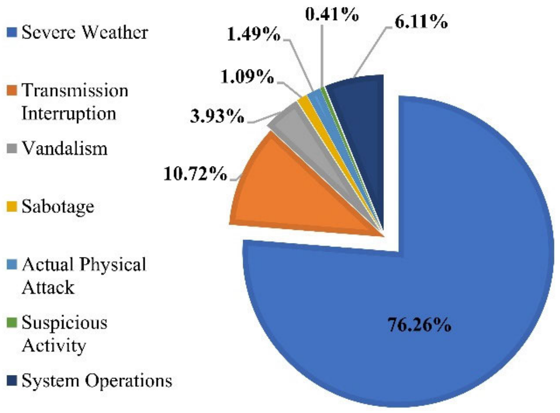

FIGURE 2. Customers affected by outages every year in the United States [14].

transmission lines must be taken down to enable grid restoration [5]. Therefore, concerns about the future of power grids worldwide need to be addressed.

Firstly, laying down long transmission lines to interconnect the population centers in sparsely populated developing countries like the Sub-Saharan countries is expensive. Therefore, the conventional way of having centralized power plants does not seem like the way to go. Secondly, the challenge comes with the rapid population growth and industrialization in many countries. This causes an exponential rise in electricity demand, resulting in billions of dollars' worth of investments in centralized power plants and long transmission lines to interconnect the loads [6], [7], [8], [9], [10]. In addition, increasing global awareness regarding increasing GHG emissions has compelled numerous countries to set ambitious targets for renewable energy integration into their power grids [11], [12], [13]. However, renewable energy sources are primarily intermittent and can further aggravate the issues of cascading blackouts and system instability.

B. MICROGRIDS

Judging from the problems outlined, it would be reasonable to consider some level of restructuring in the power grid. One such restructuring is the formation of Microgrids (MGs), implemented in relatively small geographical areas and often connected at the distribution side.

MGs can work in both grid-connected and islanded modes of operation. This allows for implementation in remote areas like rural regions, thus eliminating the need for expensive transmission lines [15], [16], [17], [18], [19], [20]. Moreover, a microgrid can isolate itself from the grid if cascading blackouts occur or in case of nearby faults in the grid. This increases the reliability and resiliency of the local systems, which is crucial to critical loads, especially during natural disasters. However, due to its smaller size, any distributed energy resource (DER) malfunction could affect the whole system if backup options like Energy Storage Systems (ESS) are poorly implemented. Other than that, some papers have classified structures such as nano-grids and open-energy systems [21], which are slight variations of the concept of microgrids. Table 1 summarizes the differences between conventional grids and microgrids.

C. LITERATURE SURVEY AND CONTRIBUTIONS

Microgrids require complex energy management systems (EMS) because they must consider the optimal operation and real-time control of the DERs to meet stability and other requisites of the microgrid. EM optimization for microgrids has had much attention in the past decade, with many ideas proposed ranging from mathematical techniques to advanced learning algorithms. Moreover, metaheuristic methods have also been applied extensively to the optimal dispatching of DERs to reduce overall operational costs. In this regard, real-time control techniques have also been researched in detail. A literature survey on this topic revealed that numerous research works have been conducted in this field. In [26], EMCS for MG is discussed for building applications, combining studies for thermal energy supply and electrical power generation. However, optimization methods are mainly limited to mathematical methods and metaheuristics. In [27], MG EMCS is critically analyzed, focusing more on MG control methods. EMS for DC MGs is reviewed in [15], [28]. In [28], more comprehensive coverage of optimization methods is given, whereas Al-Ismail [15] includes a critical analysis of the EMCS methods. The authors of [30], [31], [32], [33], [34] discussed EMCS for MGs with different classifications and contents.

Recent reviews on EMCS for microgrids are summarized in Table 2. It can be observed that most of the studies have either not included a critical analysis of the papers reviewed or only done so partially. A critical literature review is necessary to provide the readers with a clearer picture of the contents and identify the research gaps in the subject area. Moreover, most studies considered the control system strategies classified as based on methods. This is helpful in giving researchers a clear picture of which methods can be improved upon and where further novelty could be introduced.

TABLE 1. Comparisons of power grid structures (based on [170], [171]).

Structure Type	Advantages	Disadvantages
Conventional grid	• Least capital intensive as additional costs of power converters and EMCS equipment are reduced • Established rules and regulations for system operation	• In transmission faults, large grid parts are affected, leading to system instability and cascading blackouts. • Time-consuming and complex procedures for black-start operation • Less efficient in dealing with DERs • Expensive maintenance for older power plants • Higher complexity in operation coordination • Significant investments needed to supply remote areas
Microgrid	• Can isolate if there is a fault in the primary grid, improving the reliability and resiliency of the microgrid. • Ability to self-sustain allows implementation in remote areas • Can provide ancillary services to the grid operator, such as voltage and frequency support • Increased system efficiency • Better equipped for dealing with instability due to faster DER and EMCS dynamic response • Easier and less costly to maintain due to smaller network and DER size • Faster restoration from blackouts	• Require complex and expensive protection strategies • Ability to self-sustain during blackouts requires an increased generation and storage capacity • More expensive due to the increased use of power converters and controllers • Relatively fewer established standards and other regulations for system operation

However, it was observed that an application-based review is lacking in the literature for researchers who want to adopt a more practical approach toward microgrids. This would also be helpful in providing valuable insights to non-academic individuals in the power sector. Also, researchers need to work within a common framework when considering a more concerted effort to advance research in the field. The various standards accomplish this that different bodies have published. The area of Microgrids and associated EMCS research has also undergone considerable standardization. It includes topics ranging from interconnection and interoperability guides to standardization of microgrid controllers and Distributed Energy Resources Management Systems (DERMS). This helps researchers to compare new research methodologies with standardized benchmark systems on parameters outlined in the various standards. Therefore, a review of relevant IEEE standards and papers based on those standards need to be conducted to outline the work on meeting multiple requirements of the standards. This will also give readers a realistic view of what is lacking in MG EMCS research based on the associated applications.

This paper aims to cater to the gaps by providing a comprehensive and critical review of the latest papers on EMCS techniques in microgrids. Therefore, the contributions of this paper include an overview of microgrid fundamentals to provide the reader with a general picture of all the constituent parts in a microgrid, a critical review of EM optimization methods published in recent years, a review of real-time control methods for MGs, classified based on MG applications and a review of IEEE standards related to EMCS in microgrids.

D. PAPER ORGANIZATION

The following part of this article is organized as follows: Section II provides an overview of microgrid fundamentals. Section III gives a literature review of optimization techniques for the energy management of microgrids, and Section IV presents a review of real-time control methods. Section V illustrates a study of IEEE standards for microgrid EMCS; Section VI includes discussions and recommendations; Section VII concludes this article.

II. MICROGRID FUNDAMENTALS

Microgrids are defined by the IEC [35] as:

> "*a group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in either grid-connected or island mode.*"

The importance of the microgrid lies in providing reliability and resiliency to the connected loads within their boundaries and possibly providing auxiliary services to the primary grid in some cases. In addition, Microgrid aims to provide continuous service to loads following natural disasters and faults in the primary grid, especially when the grid has undergone a blackout. There are various operational aspects to consider when designing a microgrid, as outlined in Figure 3. This section provides an overview of these fundamentals as per the following.

A. MICROGRID TOPOLOGY

Various microgrid topologies and DER combinations have been reported in the literature. As per our survey, PV and Battery ESS were the most used DERs. This is perhaps because of their relatively easier installation and accessibility to the general consumer. However, whereas PV is a non-dispatchable power source, batteries are often used as controllable sources to maintain stability in the microgrid. They have been used in the grid-connected mode for general cost reduction or load shifting. In the islanded mode of

TABLE 2. Reviews published on microgrid EMCS.

Ref.	Description	EM optimization methods						Real-time control methods		Standards review	Critical Analysis
		Mathematical	Metaheuristic	Intelligent/ fuzzy	Stochastic/ Robust	MPC	MAS	Method-based	Application-based		
[26]	EMS and control for MG discussed for applications in buildings, combining thermal and electrical aspects	✓	✓	×	×	×	×	✓	×	×	×
[27]	EMS generally discussed with an in-depth focus on MG control methods	×	✓	✓	×	×	×	✓	×	×	✓
[28]	EMS for DC MG discussed in residential applications	✓	✓	✓	✓	✓	✓	×	×	×	×
[15]	EMS, control, and planning for DC MG are discussed in detail, with EMS classified based on MG operation applications	✓	✓	✓	-	×	×	✓	×	×	✓
[29]	EMS and control for MG are discussed generally, classifying based on objective functions	✓	-	-	-	-	×	-	-	×	×
[30]	EMS for MGs discussed in detail with extensive critical analysis	✓	✓	✓	✓	✓	✓	×	×	×	✓
[31]	EMS for MG discussed, in general, classified mainly into hierarchical, central, and distributed EMS	✓	✓	✓	×	×	✓	-	×	×	-
[32]	EMS and control for MG discussed in detail, with various classifications	✓	✓	✓	✓	✓	✓	✓	×	×	-
[33]	EMS for MG discussed a focus on renewable sources	✓	✓	✓	✓	✓	✓	×	×	×	✓
[34]	A comprehensive review on MG. EMS, control, and other aspects are discussed in detail	✓	✓	✓	✓	-	-	×	✓	×	-
	Current paper	✓	✓	✓	✓	✓	✓	×	✓	✓	✓

✓ Included/discussed in significant detail
- Partially included/discussed briefly
× Not discussed

operation, they were usually used for backup power during low production hours from other DERs, serving as the grid-forming DER, and in some cases, for a black start operation.

The nature of the MG and area of installation would also affect the choice of DER installed. For instance, large-scale and rural microgrids are more likely to install wind power than urban and small-scale residential microgrids, which would be more likely to go for rooftop solar PV installation. Moreover, depending on the areas of installation and the nature of the study, wind power has also been used extensively in microgrids. Another important DER employed is the diesel generator. Some studies have referred to these as the base generation for the islanded mode of operation and others as emergency generators to meet peak loads. This is mainly due to short startup timings and a stable and constant production profile. However, its downside is fuel costs and carbon emissions.

Microgrid topology and DER selection are considered within the scope of MG planning and design. Various factors must be considered when deciding on an MG architecture [36]. In this regard, the foremost decision is whether to build an AC/DC or a hybrid microgrid. This further depends on various factors such as the nature of locally available power supply, type of loads, power infrastructure, etc. For instance, if planning on transforming part of an existing AC distribution network into an MG, it would be best to use an AC Microgrid. On the other hand, if we are considering remote areas with no existing power supply and where fuel supply is also difficult, it would be better to opt for DC microgrids. This is because commonly used renewable sources are DC, and overall cost could be reduced by not considering AC-DC converters.

Moreover, decisions can be made based on the type of load to be fed, whether the microgrid is in the vicinity of or remote from a population center, and the local climate. Climate analysis determines the type of renewable generation to be deployed. Furthermore, based on the purpose of the MG and proximity to existing distribution networks, it would have

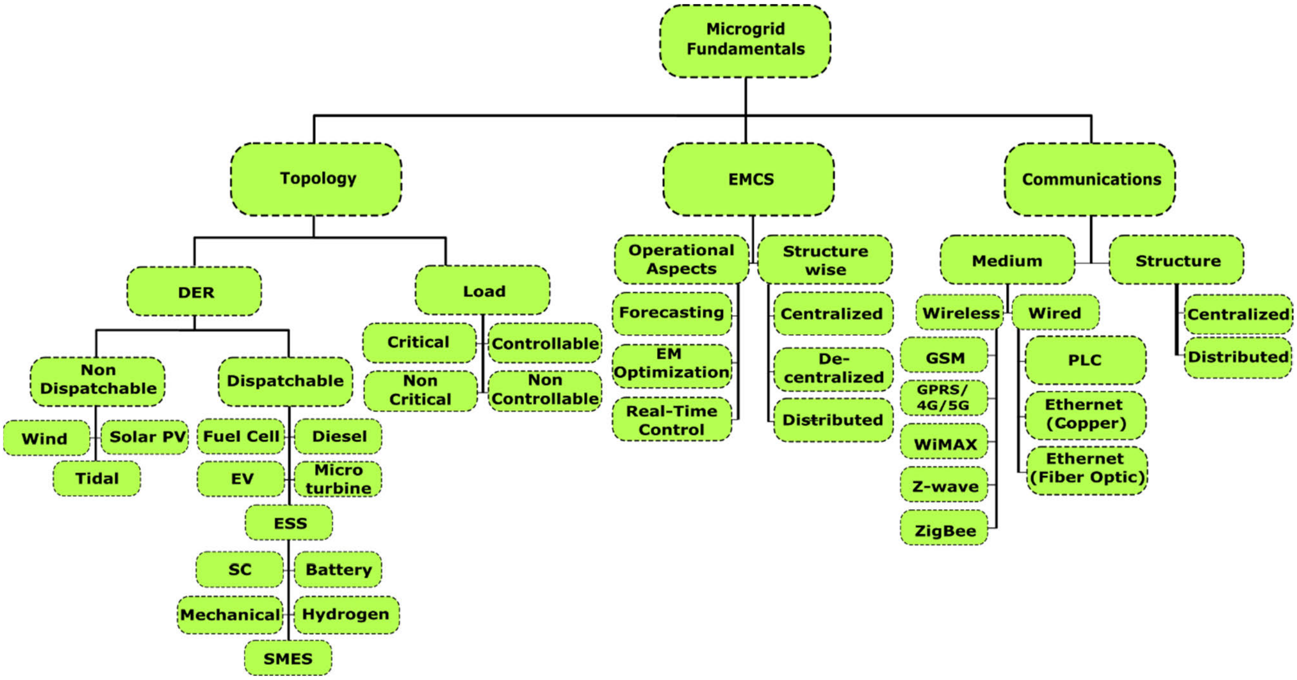

FIGURE 3. Overview of microgrid fundamentals.

to be decided whether to adopt a grid-connected MG or an islanded system.

In recent literature, the concept of a multi-microgrid system has also been proposed [37], [38], [39], [40], [41], [42]. The primary purpose of organizing such a structure is to further improve operational and economic performance, especially under disturbances occurring from intermittent renewable resources [41]. In such a system, microgrid- and multi-microgrid-level operations often have different objectives. For instance, in [40], a distribution network operator (DNO) handles the multi-microgrid system with the aim of trading with the main grid to maximize revenue. Meanwhile, the objective of each microgrid is to maximize the overall net value derived from the power consumption that the DNO traded. For further study on the microgrid structures, reference is made to [43]. It provides a detailed review of widely used microgrid architectures mentioned in the literature, classified into AC, DC, and Hybrid architectures, and comparisons.

B. COMMUNICATIONS NETWORK

A microgrid requires a communication network to enable data transfer between the various microgrid components. A good communication network ensures effective monitoring and control of the multiple DERs and loads connected to the system. Moreover, microgrids require resilient communication networks to enable rapid fault clearing and improve stability in islanding incidents.

Communication topologies can be categorized mainly into centralized and distributed systems [44]. A centralized topology uses a central server that accumulates monitoring data from the other components and provides control signals after processing, acting as a central master coordinating all the other clients in the network. A distributed system has computing capability within each DER and shares the information either with each other in a meshed structure or to a central server in the microgrid. A detailed review of the communication methods used in a microgrid was presented in [34].

One crucial issue to consider is cyber-security in microgrids since these systems increasingly rely on information and communication technologies [45]. The cyber and physical processes in smart microgrids are tightly coupled, exposing them to a wide range of cyber-attacks. These vulnerabilities may destroy critical MG infrastructure and the economy [46], [47]. Several potential examples of cyber-attacks have been identified in the literature. One such type is the Spoofing attack on Internet-of-Things (IoT) enabled EV charging stations, where the charging and thermal management systems can be manipulated to bypass cable cooling functions. This can become a fire-hazard and potentially endanger public safety [46].

A cyber-attack on DERs can also result in a loss of revenue when dispatchable sources become unavailable or do not perform according to the optimally scheduled power exchange determined by the EMS. This can happen due to false-data-injection attacks, where manipulated data is fed into the EMS, causing system failure or inefficient operation. In addition, there can be attacks on data availability at critical times in various MG components. For instance, data transfer to protection relays can be delayed, proving catastrophic during power faults. Moreover, hackers can also exploit system

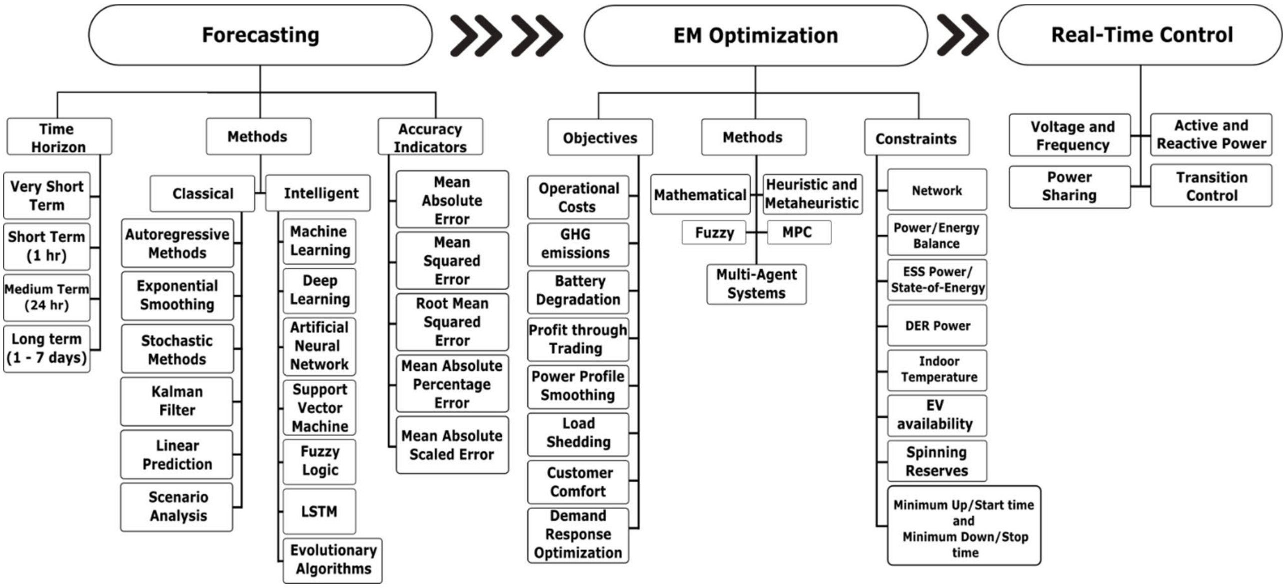

FIGURE 4. Three stages of energy management and control strategies.

vulnerabilities arising from co-habiting legacy and new systems [47].

Various steps can be taken to ensure safety from cyber-attacks. For example, the physical security of microgrid assets should be guaranteed, and proper personnel training on the safe use of sensitive assets should be done periodically. Additionally, plans for system recovery should be established to minimize system downtime. Moreover, various cyber-security technologies developed in the last few years to protect industrial control systems should be implemented and updated. These technologies include establishing and managing cryptographic keys in Advanced metering infrastructure (AMI) components and power converters for secure data transfer, security monitoring systems, and control strategies that are resilient to cyber-attacks.

C. ENERGY MANAGEMENT AND CONTROL SYSTEM

An EMCS is an integral part of a microgrid, mainly because of the distributed nature of its energy resources. An EMCS aims to optimize the usage of the different resources to achieve specified objectives within system constraints through centralized, decentralized, or distributed computation. Secondly, the EMCS must effectively apply the previous computations to the microgrid system. This is achieved using a real-time control system that involves the operation set points generated by the EMCS. Most EMCS often work in a flow that includes forecasting data, feeding the results to EM optimization, and producing operational setpoints to be implemented by the real-time control stage, as described in Figure 4. This section outlines various EMCS structures and highlights their operational flow in microgrids.

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1) EMCS STRUCTURE

EMCS structure classification depends on how the computing platforms and associated communications networks are organized for operation. For example, it might be a centralized, decentralized, or distributed structure. In centralized systems, the management system is located in a central station and connected to the DERs via communication lines. The DER measurement and status data are sent to the EMCS server, where the monitoring and control computations occur, and commands are then sent to the DERs for execution.

The EMCS can also be connected to other ancillary workstations, such as distribution network operators or forecast stations, depending on the system architecture. While this setup is better at overall supervision of the whole system and achieving global optimization, issues could be anticipated with system expansion and entire system breakdown in case of EMCS or communication faults. In decentralized systems, each DER operates independently and manages itself using a local controller, thus eliminating the need for communication. The controller takes local measurements such as bus voltage, frequency, and DER power output. The DER uses this data to implement proportional power sharing and maintain

TABLE 3. Comparison of EMCS structures.

Structure	Description	Advantages	Disadvantages
Centralized	All processing and decisions are taken at a central station, where each DER sends operational data. Suitable for smaller microgrids	• More effective at global optimization • Focused point of maintenance • Easier monitoring and control of the whole system • Easily applicable hierarchy in operations • Well-established communication and operation protocols	• Cannot function without a communication network • Communication lines can become expensive • Slower response • Heavy computational burden • Problems with the expansion of the system • Single point of failure
Decentralized	Each DER has a local controller. All control functions are carried out independently, without the need for communication. Bus frequency or voltage is often used for power sharing or voltage support. Suitable for larger microgrids	• More reliable because a communication network is not required • Faster control response • System modularity, flexibility, and plug-and-play capability improved • Cheapest option • Better suited against cyber-attacks	• Problems with the drift of system setpoints can occur. It will then require a secondary control system (which is usually centralized and therefore requires communication) • Offers limited capabilities. There is no option for global optimization • Little to no overall MG supervision • Prone to instability and require fast synchronization
Distributed	Highly connected system, where each DER has its computing capability. All local controllers also interact with each other and possibly a central controller to manage different tasks. Suitable for larger microgrids	• Improved redundancy and robustness as another controller can take over for DER in case of failure of the local controller • Improved reliability of EMCS • Fast control response • Better for scaling up the system • Better suited against cyber-attacks • Computational burden shared between the various DERs	• Most expensive option due to the requirement of a more comprehensive communication network. • Difficult to monitor and manage due to multiple entities participating

microgrid stability. However, after the extended operation and facing disturbances, the DER operational setpoints can drift from stable values and require resynchronization across DERs.

The advantages of centralized and decentralized structures can be combined in distributed systems, and the drawbacks can be covered. Each DER has its computation capability in the local controller while communicating with adjacent DERs and possibly a central EMCS server. This method usually requires minimal communication bandwidth and can also provide improved system redundancy as neighboring controllers can compute for each other in case of failure. Multiple communication paths can also be set up to facilitate this. However, this option also comes with the added expense of redundant communication links and distributed computation. The three types of structures of EMCS are summarized in Table 3 and demonstrated in Figure 5.

However, whereas these three can be considered basic categorization of control structures, most microgrid EMCS employ a combination of these elements for applications of different timescales. This is called hierarchical control and comprises of primary, secondary, and tertiary levels, depending on the operational timescales. The primary control operates at the millisecond scale and comprises of control objectives such as voltage, frequency, current regulation, maximum power point tracking (MPPT), and power sharing. This control is usually decentralized because it is implemented locally in each DER. In secondary control, timescales may range from seconds to minutes and include applications such as voltage and frequency reference correction, power dispatching, and transition control. Again, this control is either centralized or distributed. Finally, tertiary control operates on timelines of hours to days, including energy trading applications, unit commitment, and forecasting generation and load demand.

2) FORECASTING

An EMCS must ensure that the microgrid's resources are utilized most efficiently and cost-effectively. For this, it needs to forecast three types of profiles with reasonable accuracy: load demand, power generation, and grid electricity prices. With this information, the EMCS can optimally dispatch resources such as ESS and diesel generators. An EMCS will have to forecast the load consumption for the day ahead, analyze the expected weather and subsequent generation from renewable sources, and then decide when to prioritize ESS charging and trade with the primary grid. This results in better stability and reliability, providing smooth power profiles.

The forecasting horizon for a microgrid can range from a week to a day ahead to an hour or a few minutes depending on the methodology utilized in the EMS. Much work has been done on forecasting methods for microgrid applications in the literature. For example, Agüera-Pérez et al. [48] provide an overview of using meteorological data for weather forecasting in microgrids for generation and load predictions and the resulting implications on EMCS. Besides, comparisons and discussions of existing literature on the topic are also covered in detail. Aslam et al. [49] present and discusses state-of-the-art intelligent learning methods for solar energy forecasting for EMS.

A review of wind energy forecasting techniques for microgrids is covered in [50], categorizing the various methods into statistical and intelligent algorithms. Besides, power generation forecasting from wind and solar PV DERs is discussed in [51], and the related literature was reviewed. The authors have categorized papers based on different

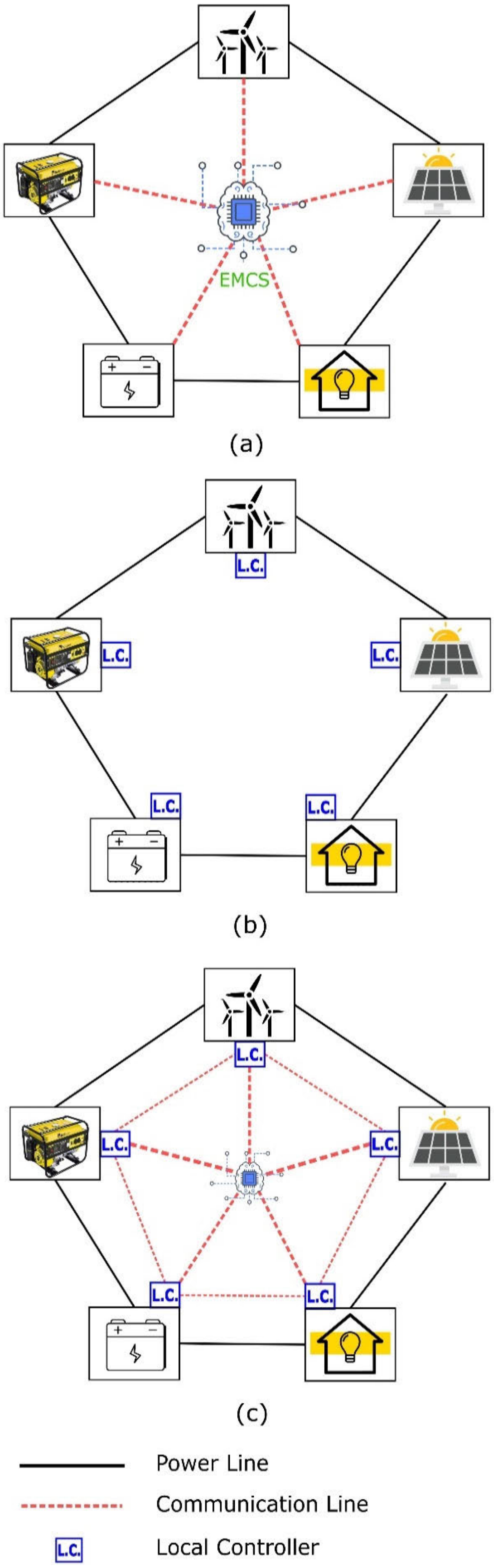

FIGURE 5. **(a) Centralized structure (b) Decentralized structure (c) Distributed structure.**

forecasting horizons: very short-term (from seconds to half an hour), short-term (half an hour to 1 hr.), medium-term (1hr–24hr), and long-term (1 d–1 week). According to the paper, very short-term forecasting aims at achieving dynamic control for renewable power generators and load tracking. Short-term forecasting is used for scheduling energy flow among power sources, loads, and storage devices, whereas medium-term and long-term forecastings are responsible for price settlement, load dispatch, and maintenance scheduling, respectively. Moreover, Aybar-Mejía et al. [52] focus on reviewing both generation and demand forecasting algorithms to achieve effective energy balance in the microgrid. This is because effective energy balancing depends on reliable energy generation and the reserve available always to ensure supply and meet expected demand.

3) SYSTEM MODELLING AND MATHEMATICAL FORMULATION

Whereas this portion does not necessarily lie in the operation process of EMCS, data from forecasting the various profiles are supplied to the mathematical models of the microgrid system in the controller. The system modeling and mathematical formulation are usually carried out during the design stage of EMCS. However, some systems may be designed, so that problem formulation occurs during operation, such as in the case of connection or removal of load/DER or changes in network topology. Further, this stage may include theoretical formulation of the problem into objective functions and system constraints and then developing it into the necessary code for the EMCS controller. A generic problem formulation takes the form of (1).

$$\begin{aligned} &minimize\ Objective\ function = \sum_{t=1}^{T}\sum_{i=1}^{N} F_i(t) \\ &subjected\ to\ (s.t.):\ g_i(t, t-1) = 0 \quad \forall i,\ \forall t \\ &\qquad\qquad\qquad\quad h_i(t, t-1) \leq 0 \quad \forall i,\ \forall t \\ &\qquad\qquad\qquad\quad b_j(t) = 0 \quad \forall j \end{aligned} \tag{1}$$

where, F_i represents the cost function of device i, N is the number of devices, and T is the time horizon for scheduling. g_i and h_i are respectively the equality and inequality constraints of device i. b_j represents the power balance equations for bus j. The main aim of an optimization problem is to minimize or maximize the objective function based on the nature of the problem. During the operation process, data from the forecasting stage may then affect the different variables or the constants of the equation (1).

4) OPTIMIZATION AND REAL-TIME CONTROL

In this step of the process, the mathematical problem is solved. Firstly, the optimization of different objective functions depends on the EMCS design. Numerous methods have been attempted to solve the optimization problems of EMCS. Broadly, these methods can be classified into mathematical, fuzzy, predictive, multi-agent-based, and metaheuristic methods. Usually, the output of this stage provides setpoints for the local control of various DERs connected in the system. Real-time control systems then execute the reference values. This stage can have voltage and frequency control, power

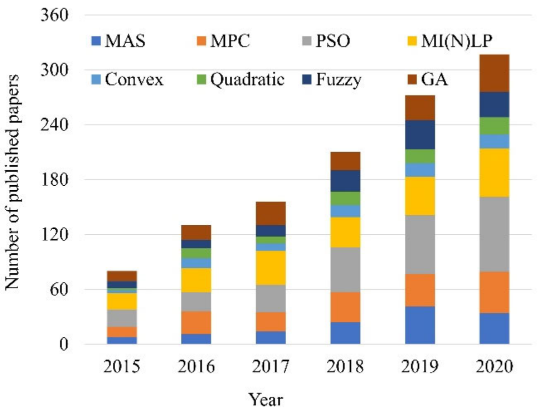

FIGURE 6. Number of papers published on EM optimization methods (Source: Scopus).

(or current) control, power sharing control, and transitioning control of the microgrid or DERs between grid-connected and islanded modes.

III. EM OPTIMIZATION

Microgrids comprise of multiple sources of generation, all with varying operational costs and technical limitations. To maintain a continuous supply and ensure the cost-effectiveness of the microgrid, it is essential to operate the DERs in a manner that provides the most significant benefits. In grid-connected mode, usually, the aim is to maximize the profits of the microgrid system by trading with the grid and effectively utilizing the available DERs to achieve this. In islanded mode, the objective could change to ensuring maximum operation time without external grid support, for instance. All this is done using an energy management system that utilizes various optimization algorithms to schedule the resources based on predefined objectives. Figure 6 shows the methods used in the past few years to solve optimization problems. This section reviews the recent literature on various EM optimization techniques.

A. MATHEMATICAL METHODS

1) MILP AND MINLP

Mixed Integer Linear Programming (MILP) is an optimization and system analysis tool for problems that have a mix of integer and non-integer variables, thereby providing a flexible and robust method for solving large and complex problems [53], [54], [55]. In microgrids, continuous variables such as power generation or exchange with the grid form non-integer values, whereas the state of microgrid components such as grid-connected/islanded mode and ESS charging/discharging states, among other states, can be formulated as binary or integer variables. Ref. [56] proposes an EMS for an Energy Hub to reduce operational costs based on day-ahead optimal scheduling. The objective function of the problem formulation is shown in (2).

$$min \sum_{t=1}^{T} C_t^{CHP} + C_t^{ST} + C_t^{shed} + C_t^{Heat} \tag{2}$$

where, C_t^{CHP}denotes the cost associated with Combined Heat and Power units, C_t^{ST} denotes cost/revenue associated with buying and selling to the grid, C_t^{shed} denotes the cost of load shedding and C_t^{Heat} is the cost of heat loads. Moreover, a linearization approach is used in this paper for the AC network model line flow equations, as shown in (3) and (4).

$$l^P_{(i,k)t} = g^L_{(i,k)}\left(V_{it} - V_{kt} - \psi_{ikt} + 1\right) - b^L_{(i,k)}\phi_{ikt} \tag{3}$$

$$l^Q_{(i,k)t} = -b^L_{(i,k)}\left(V_{it} - V_{kt} - \psi_{ikt} + 1\right) - g^L_{(i,k)}\phi_{ikt} \tag{4}$$

where, $l^P_{(i,k)t}$ and $l^Q_{(i,k)t}$ are line power flow equations from bus i to bus k, $g^L_{(i,k)}$ and $b^L_{(i,k)}$ are the conductance/susceptance of the lines, and V and ϕ are the voltage and angle difference between the buses. Ref. [57] uses MILP to optimize a BESS in a grid-connected microgrid to reduce energy costs. Power flows between grid, loads, and PV panels are considered non-integer variables, and ESS states (charging/discharging) are considered binary variables.

Mixed Integer Nonlinear Programming (MINLP) is similar to MILP described previously, except that this is used for problems where the feasible region of the problem is non-linear, depicting real-world problems more accurately [58]. In microgrid applications, a non-linear model of the network would be used in the problem formulation. For instance, (5-6) present the non-linear equations in ref. [56], from which equations (3-3) were derived.

$$\begin{aligned} l^P_{(i,k)t} = g^L_{(i,k)} \Big(& V_{it}^2 - V_{it}V_{kt}\cos(\phi_{ikt}) \\ & - b^L_{(i,k)} V_{it} V_{kt} \sin(\phi_{ikt}) \Big) \end{aligned} \tag{5}$$

$$\begin{aligned} l^Q_{(i,k)t} = -b^L_{(i,k)} \Big(& V_{it}^2 - V_{it}V_{kt}\cos(\phi_{ikt}) \\ & - g^L_{(i,k)} V_{it} V_{kt} \sin(\phi_{ikt}) \Big) \end{aligned} \tag{6}$$

In [59], an EMS for a grid-connected home-level microgrid is designed, dealing with both thermal and electrical loads. MINLP is used due to the non-linear nature of the objective cost function and power flows. Ref. [60] presents an EMS for an urban microgrid to maximize self-consumption and provide ancillary services to the grid.

2) QUADRATIC PROGRAMMING

Quadratic programming (QP) problems are a subset of non-linear programming encountered in many real-world scenarios. QP usually has a quadratic cost function and linear constraints. Moreover, many non-linear problems require the solution of a QP subproblem at every iteration [61]. One of the major examples of power systems utilizing quadratic models is thermal generators, with a general cost function of (7).

$$Cost = a_0 + a_1 P + a_2 P^2 \tag{7}$$

where, a_0, a_1, and a_2 are the cost coefficients, and P is the active power output of the generator.

In [62], a scheduling framework for residential microgrids comprising of energy-based and comfort-based controllable loads, ESS, and renewable sources is proposed. Due to the quadratic dynamic pricing scheme, MIQP is used to optimize controllable loads and charging/discharging strategies of the ESS and PEVs. Ref. [63] considers diesel generator fuel consumption, degradation of battery ESS, carbon emissions, load shifting, and load curtailment in the MIQP problem formulation to the real-world application of Semakau island near Singapore. Ref. [64] provides a complementary convex QP method for reducing computational burden when applied to district energy systems compared to mixed integer programming.

3) LAGRANGE MULTIPLIERS

Lagrange Multipliers are one of the most basic methods of mathematical optimization. It is suitable for finding the local maxima and minima of a function without first solving the constraint equation for one of the variables [65]. In [66], a real-time EMS is proposed for the rooftop PV panels with battery ESS (BESS) to maximize revenue. Lagrange multipliers are used to solve the optimization problem and compared with a dynamic programming approach using the formulated Lagrange function as in (8):

$$L = \sum_{t=1}^{T} P_{g,t}\pi_{g,t}\Delta t + \sum_{t=1}^{T} \lambda_t \emptyset_t + \gamma\varphi \tag{8}$$

where λ_t and γ are Lagrange multipliers, $\emptyset_t$ and φ are equality constraints and $P_{g,t}\pi_{g,t}\Delta t$ is the cost/revenue from the grid. The partial derivative of (8) with respect to the independent variables is then equated to zero to find the solution to the problem.

A bi-level EM for a multi-microgrid system is presented in [37]. The objective of the system is to maximize the profits of the microgrids and then distribute the profits fairly using a profit-quantity curve. Alsalloum et al. [67] aim to solve the microgrid local consumption optimization problem using the Stackelberg game method, using Lagrange multipliers to define the optimal energy demand.

4) CONVEX OPTIMIZATION

Convex optimization is concerned with minimizing problems that can be formulated as convex functions. The generator cost functions are one of the power systems' most common convex functions. Convex optimization is a larger field with subsets that include Linear programming and Least squares, for instance [68]. A review of convex optimization methods for achieving near-net zero buildings is done in [69]. In [70], convex optimization is used to minimize the microgrid's daily cost of operation and smoothen the power exchange profile with the utility. Rahim et al. [71] propose a robust, decentralized, and real-time EM system where the power dispatching problem is formulated using a convex optimization problem and solved using the sub-gradient method. In [72] and [73], to solve the problem, first, a unit commitment non-convex problem is formulated and then transformed into a convex problem using relaxation methods.

5) DYNAMIC PROGRAMMING

Dynamic programming (DP) is a method that divides a problem into sub-problems to reduce complexity and then solves the subproblems separately. Ref. [74] uses DP for optimal day-ahead scheduling of a DC microgrid. It is shown that the DP-based approach reduces the complexity of the problem while giving reasonable results. An EMS for a residential hybrid renewable energy system using a two-stage control system is presented in [75]. First, an offline predictive DP-based optimization stage reduces operational costs by determining the best charge/discharge timings for a BESS and Hydrogen ESS. Then a real-time rule-based controller is used to determine the system's real-time operation based on computations from the first step. Ref. [76] proposes a stochastic DP approach to solve the optimization problem of an islanded microgrid. The authors of Ref. [77] aimed to reduce the computational load for the EMS by proposing a real-time rolling horizon strategy and Model Predictive control in shorter time steps for DP instead of global optimization for ESS setpoints to achieve optimality. Finally, ref. [78] proposes a multi-parametric and multi-objective dynamic optimization problem for tackling economic and environmental objectives.

6) STOCHASTIC AND ROBUST PROGRAMMING

According to [79], stochastic optimization problems could have two properties. Firstly, there is random noise in the variables being optimized. Secondly, there is an arbitrary choice in the search direction as the algorithm iterates toward a solution. In other words, stochastic optimization concerns itself with problems with some degree of randomness in the variables or the objective function. This method is prevalent in EMCS because of the stochastic nature of renewable generation, load demands uncertainty, and the dynamic pricing systems being introduced.

In [80], EMS is implemented in an Energy Hub with the objective of cost minimization and reduction in emissions. This is done in two steps: Stochastic optimization to cater to the uncertain nature of renewable energy sources (RES) generation and load consumption, and a fuzzy approach to reduce a multi-objective optimization to single objective optimization and solve the final problem. Ref. [81] proposes an EMS for an MG to reduce the cost of operation, keeping in view the consumer/household's comfort. In [82], stochastic risk-constrained scheduling of islanded MG is performed to maximize the operator's profits. EMS is proposed in [38] for a multi-microgrid system that uses stochastic optimization to minimize operation costs and unexpected power exchanges with the grid. The system level control decides the scheduled power trajectories based on forecasts of power balances, whereas MG level control decides the charging/discharging operation of storage units based on load and renewable energy systems (RES) forecasts. Finally, local control takes care of the real-time output of generating units based on voltage and frequency.

B. META-HEURISTIC METHODS

Meta-heuristic algorithms are problem-independent techniques that can be applied to a wide range of problems, with purpose-appropriate values for the decision variables of an optimization problem so that the objective function is optimized. They can solve all well-posed real-world and complex problems that other optimization methods, such as linear and nonlinear programming, dynamic programming, and stochastic dynamic programming, struggle with. For this reason, meta-heuristic algorithms have become a preferred solution approach for most complex engineering optimization problems [83]. A review of these methods is presented here in this section.

1) EVOLUTIONARY ALGORITHMS

Inspired by Charles Darwin's theory of natural evolution, these algorithms reflect the process of natural selection, where the fittest individuals are selected for reproduction to produce offspring of the next generation. In [84], a hierarchical Genetic algorithm (GA) based EMS is proposed for a grid-connected microgrid to maximize the profit generated by the energy exchange with the grid under a time-of-use pricing policy. A generic pseudocode for Evolutionary Algorithms like the genetic algorithm is presented in Algorithm 1.

Algorithm 1 Evolutionary Algorithm Pseudocode

```
Set $P_e$, $P_s$, $P_c$, $P_m$
Set Generation $i = 0$
**Initialize** Random Population
Compute the **fitness** of the population using the fitness function
While termination criteria are not met, do:
    Set up population matrix for $i + 1$
    Perform **Elitism**: Select the best individuals and copy them into generation $i + 1$, with probability, $P_e$
    Perform **Selection**: Pair up individuals from generation $i$ for reproduction with probability, $P_s$.
    Perform **Crossover**: Produce children from two individuals of generation $i$ with probability, $P_c$
    Perform **mutation**: Randomly select a gene of an individual and set it to another random number with probability, $P_m$.
    Compute **fitness** of generation $i + 1$
    Check the **termination criteria**
    Set $i = i+1$
```

Silva et al. [85] presented an EMS for microgrid using the non-dominated sorting genetic algorithm (NSGA) III for a better demand response strategy in combination with optimizing battery use to minimize energy costs and environmental pollution while considering user comfort. An EMS for a standalone microgrid is proposed in [86] based on a new genetic algorithm to narrow feasible regions of the involved variables. The algorithm is used to perform effective economic dispatch of the connected DERs. The NSGA method is also used in [87], [88] to optimize the EMS for grid-connected microgrids. In [40], an Artificial Immune System algorithm (AIS) is used to solve a multi-objective formulation for a multi-microgrid system for maximizing revenue and optimizing the power distribution in the multi-microgrid system.

2) SWARM OPTIMIZATION

These algorithms optimize a problem by iteratively trying to improve a candidate solution concerning a given quality measure. A three-level hierarchical control structure is proposed in [89] to realize multi-objective optimal control for a DC microgrid. At the primary level, a decentralized virtual battery-based droop control is introduced to multiple ESSs, where the power dispatch among ESSs is achieved autonomously. An improved particle swarm optimization (PSO) algorithm is applied to obtain the optimal setting of the virtual-battery model parameters for minimum daily operating costs. Ref. [90] proposes a multi-agent control system for a hybrid microgrid where PSO is used to optimize each agent (Each DER with computing capability installed is considered an agent). The EMS aims to optimize the operational and economic needs of the AC grid, DC grid, and system operator. For this purpose, agents interact with each other to achieve optimal operation of the whole microgrid. The research work in [91] proposes a hybrid genetic PSO (HGPO) algorithm and existing algorithms like a genetic algorithm (GA), binary PSO (BPSO), ant colony optimization (ACO), wind-driven optimization algorithm (WDO), bacterial foraging algorithm (BFA) to schedule smart appliances optimally, to minimize electricity costs and carbon emissions, and to improve peak to average ratio profile.

3) MATHEURISTICS

Matheuristics are a class of optimization algorithms that combine the benefits of mathematical programming and heuristic algorithms such that mathematical algorithms can derive benefits from the inclusion of heuristics in minimizing the search space and use of mathematical programming in deriving more accurate solutions within a heuristic framework [92], [93], [94]. These algorithms have been given increasing attention in operational research for various applications such as vehicle routing problems and wind farm configuration, among others [95], [96], [97].

The use of Matheuristics in microgrid EMS is still relatively recent, with only some studies conducted. Ref. [98] proposes an EMS for handling the emergency response to faults and consequent islanding incidents to minimize the cost of interrupting critical loads. A heuristic is used to manage the network model and load prioritization, and MILP is then used to solve the optimization problem. In [99], a multi-start greedy heuristic is combined with a local search algorithm executed by a mixed-integer programming solver to schedule smart appliances in smart homes. Umetani et al. [100] presented a MILP-based heuristic algorithm for EV charge/discharge scheduling in building EMS on a time-space network model to reduce peak load. This method involves rounding a fractional solution of the Linear Programming relaxation problem to attain a feasible integer solution to the MILP problem. In [101], a smart home EMS is developed using the adjustable-robust-MILP algorithm, integrated with heuristics to correct real-time operation values by imposing a penalty function.

C. FUZZY OPTIMIZATION

Fuzzy optimization deals with problems where uncertainty is involved and utilizes logical reasoning to make decisions. However, the parameters involved do not necessarily have to be binary, as fuzzy programming can deal with values between two extremes, thus allowing more flexibility. Ref. [102] presents a microgrid with a fuzzy-based power management system that calculates the various power references based on ESS State-of-Charge (SoC) and load requirements and feeds these references into the lower level of control, where a non-linear barrier function-based first-order sliding mode control (NBF-SOSMC) regulates the currents of the connected sources. In [103], a low complexity fuzzy logic control is applied to an Electro-Thermal microgrid with uncontrollable loads to smoothen the power exchange profile with the grid and conduct demand side management of an Electric Water Heater. Thirugnanam et al. [39] propose an EMS for the multi-microgrid system to reduce consumer energy consumption costs using a fuzzy peer-to-peer energy exchange algorithm under dynamic pricing. In [104], a microgrid's EMS and control system is developed using a neuro-fuzzy wavelet-based controller implemented in the power inverters. The system is set up in a hierarchical lower-top structure where the top level utilizes real weather and load patterns, whereas the bottom level controls the energy resources and power converters.

D. ARTIFICIAL NEURAL NETWORKS

Artificial Neural Networks (ANN) algorithms were also used to tackle the EMS problem of microgrids. These algorithms mimic the structure of the brain by constructing input-output parametrized networks that model the problem at hand. An optimization procedure is implemented to obtain the optimal parameters for the network. Once the network is optimized (or trained), optimal solutions for the problem can be obtained in fast computational times. Neural networks typically contain three main stages: the input layer, which receives the input data, the hidden layer, which processes the data based on various predefined functions and the output layer, as depicted in Figure 7. The hidden layer may include multiple further layers, depending on the design of the neural network.

Wang et al. [105] proposed a Lagrange programming neural network to optimize the scheduling of an MG, where variable neurons are combined with Lagrange neurons to minimize total operational costs and maximize the power generated by renewable sources. Moreover, a radial basis function neural network is also employed to predict renewable generation and load demand. Ref. [106] presented an evolutionary adaptive dynamic programming and reinforcement learning framework to train EMS for MG online. This method uses two neural networks: the first provides the optimal control signals, while the second evaluates the performance and ‘‘criticizes’’ the first network. Both networks are implemented using a multi-layer perceptron feedforward neural network. Ref. [107] implemented a recurrent neural network for the optimal operation of an MG under a multi-agent system framework, where each source is modeled as an agent that sends information to a central EMS. In [108], the EMS is modeled as a Markov Decision Process. A deep reinforcement learning algorithm is then used to solve the problem to minimize the operational cost of the MG. In [109], a concurrent neural network estimates the daily operating cost of a multi-MG system. The authors of [110] proposed a data-driven deep neural network and model-free reinforcement learning technique to optimize the peak-to-average ratio and maximize the profit of a multi-MG system.

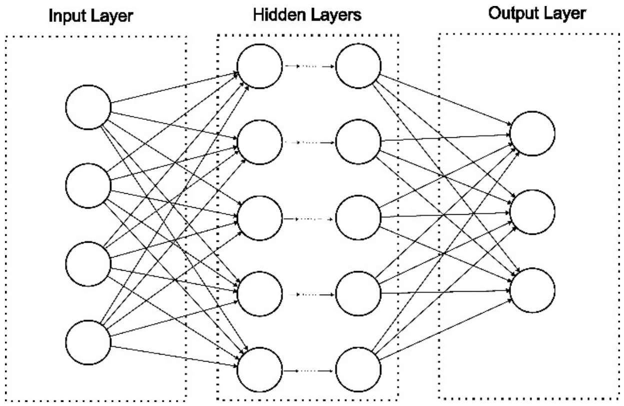

FIGURE 7. Structure of a typical neural network.

E. MODEL PREDICTIVE CONTROL

Model predictive control (MPC) is a process control scheme that uses the model itself to predict future model states over a time window known as the time horizon. It is also known as receding horizon control. In [111], EMS is developed for a cluster of islanded MGs, with the objective of optimal energy scheduling, keeping the renewable generation and load uncertainties in view. A robust method based on Tube MPC is proposed for this purpose. The problem is formulated as a multi-stage optimization model and is solved using a newly devised decentralized Compound Alternating Direction Method of Multipliers algorithm. In [112], MPC is used for scheduling interconnected microgrids with the objective of optimal scheduling for energy dispatch to the grid in real-time markets, keeping in view emergencies where microgrids might incur penalties from the operator for not delivering power as agreed due to renewable intermittency. A local energy market can be established to trade between MGs in case of islanding under grid fault conditions. In [113], control of a distribution network structured into microgrids is proposed, with the primary objective of providing flexible services using available BESS and Hydrogen ESS. Ref. [114] also proposed a two-level EMS, focusing on reducing operating costs and maximizing local energy consumption in the microgrid while maximizing user and distribution grid operator benefits. Ref. [115] proposed real-time optimization using a data-predictive control framework. A cooperative distributed MPC optimization is used to dispatch a multi-microgrid system. The authors of [116] used MPC-based energy scheduling that exhibited improved performance over a fuzzy-based heuristic scheme due to its ability to make decisions accounting for the future generation and load demand. In terms of computational requirement, however, MPC was more demanding than the fuzzy scheme.

F. MULTI-AGENT SYSTEMS

Multi-agent systems (MAS) are models that consider various microgrid components as "agents." These agents are designed to interact with each other to make decisions regarding multiple objectives. MAS can be used to optimize various microgrid objectives where different resources can form consensus over operating points to achieve optimal operation. Considering the different operating conditions of the MG, the performance of the MAS responsible for the secondary control was analyzed by co-simulation involving the software PSCAD and PADE platform [117]. The co-simulation enables the exchange of simulation data, communication between agents, and commands sent to the microgrid in real-time, thus providing a more realistic environment for MG control and management. In [118], an EMS is proposed for Tetouan city in Morocco to reduce the operation cost and maximize benefits by trading with the primary grid. Refs. [119] and [120] consider EMS for a hybrid microgrid, where MAS schedules EV charging/discharging to trade with the grid and minimize operational costs effectively. Ref. [42] uses hierarchical Stackelberg Game Theory, incentive-based Demand Response, and MAS to maximize the benefits of a multi-microgrid cluster, aiming for a win-win scenario between the MG cluster, the individual MGs, and the users. Table 4 summarizes the microgrid EM optimization methods.

IV. REAL-TIME CONTROL

In real-time operation, parameters such as voltage, frequency, and power need to be regulated and controlled according to pre-decided setpoints to ensure the stable operation of the microgrid. Sometimes, this is performed by the control system of the DERs, or a central microgrid control system. Microgrid control applications include system voltage-frequency control, DER active-reactive power control, power sharing control of the DERs, and transition control of the microgrid and DERs. This section reviews real-time control methods categorized based on control applications in the literature.

A. VOLTAGE AND FREQUENCY

Voltage (V) and frequency (F) controls are essential for a microgrid to operate in islanded mode or provide ancillary services to the main grid in grid-connected mode. In rotor-based generators such as diesel or thermal power plants, voltage is controlled through the injection or absorption of reactive power by varying the excitation current. Similarly, frequency is controlled by injecting or absorbing active power from the grid. However, the DERs are predominantly inverter-based due to using renewable sources and BESS. Therefore, control schemes have been implemented to vary the pulse-width-modulation (PWM) signals to the inverters for the required V-F profile.

In [121], an optimal cooperative voltage regulation controller is designed for secondary stage control to enhance system performance against constant time delays that can arise due to communication between DC microgrid components, which helps prevent battery degradation and improve the stability of the microgrid. To achieve this, the battery storage system regulates the DC bus voltage as per (9) and (10).

$$I_{ref} = I_d(V_{DC})g_{fc}(V_{DC})g_{fd}(V_{DC}) \tag{9}$$

$$I_d = -k_D \mathrm{x}(V_{nom} - V_{DC}) \tag{10}$$

where, $I_d(V_{DC})$ is the linear dc-bus voltage droop term, and g_{fc} and g_{fd} are the BESS fast charge and discharge terms. k_D, V_{nom} and V_{DC} represent the droop coefficient, reference bus voltage, and actual bus voltage, respectively.

Ref. [122] proposes decoupled control strategy for batteries and super-capacitors based on a Type II controller and non-linear PI controller, respectively, to regulate bus voltage and power quality during transient/abrupt power variation in a low-voltage DC microgrid. Wang et al. [89] implement a secondary voltage control in a DC microgrid to suppress transient voltage fluctuations due to the decentralized local power controllers implemented in the DERs. This secondary control system is implemented in a centralized structure with communication between DERs and a central controller for more effective voltage regulation.

In [123], a control system is proposed for DC microgrids where an AC voltage signal is superimposed onto the DC voltage of the microgrid. The frequency of this AC voltage is then used to control other Distributed Generators (DGs) in a decentralized manner using droop control in a master-follower control scheme, with one DG acting as master. Ref. [124] proposes a combination of a non-linear adaptive droop controller and MPPT to regulate the voltage of the DC bus in the islanded mode of operation and when the microgrid is transitioning in connection to the grid, prioritizing MPPT control to maximize RES utilization. Moreover, the adaptive parameters of the droop controller are optimized using sequential quadratic programming. Ref. [125] utilizes a Fractional Order PID controller to regulate the DC bus voltage in a hybrid microgrid for remote and islanded operation. In [126], normalized gradient adaptive regularization factor neural filter-based control is used for a PV-BESS-based AC microgrid to regulate the DC link voltage of the voltage source converter to achieve maximum power extraction from the PV.

Voltage control in the secondary control stage under a distributed multi-agent system structure is proposed in [130] to regulate voltage and frequency and correct any V-F deviations caused by the droop controller from the primary control stage.

TABLE 4. **Review of microgrid EM optimization methods.**

Ref.	Method	Year	EMS Structure	DER Type [Microgrid Type]	Forecast Method	Reported Contributions	Limitations/Future Work
[56]	MILP	2019	C	WT-CHP-BESS-Thermal ESS-Grid (On/Off) [AC]	N/A*	• EMS proposed for Energy Hub to minimize operation costs • Considered thermal and electric MG together in scheduling • Linearizing the problem formulation to reduce computational complexity	• BESS degradation and GHG emissions cost not considered • Computational efficiency improvements of the proposed method were not reported
[57]	MILP	2020	C	PV-BESS-Grid (On) [AC]	Online LSTM + rolling horizon strategy	• Economic load dispatch problem presented minimized energy costs and maximized BESS life • 24 hr. forecast combined with dynamic hourly forecast to reduce overall prediction error in scheduling, resulting in a 3.3% cost reduction over offline methods	• Power export to the grid and MG islanding were not considered • Variable tariff needs to be on smaller timescales for RES trading. • Network constraints not considered in scheduling
[59]	MINLP	2021	C	PV-BESS-PHEV-CHP-Grid (On) [AC]	Scenario Analysis	• EMS designed for home-level MG to minimize the cost of operation • CHP units were used for a combined thermal and electric EMS to reduce operational costs • Reported that TOU pricing results in the lowest operation costs compared to fix and RTP. Total cost reduction of 20% as compared to heat-led control	• BESS degradation and GHG emission cost were not considered. • MG islanding was not considered • Computational complexity not investigated
[60]	MINLP	2021	C	PV-BESS-Grid (On/Off) [AC]	Deep learning of historical data using LSTM	• EMS for urban MG to maximize self-consumption, minimize operational cost and provide ancillary services to the grid using optimal power flow • Significant reported cost reductions (40-70%)	• Battery power constraints and degradation costs were not considered. • Transmission power losses not considered • Computational complexity not investigated
[64]	QP	2019	C	PV-Gas Turbine-Diesel Generator-FC-BESS-Grid (On/Off) [AC]	N/A*	• EMS for the district energy system to minimize operational costs • Significant reduction in computational load of the dispatch problem with convex-QP formulation, as compared with mixed integer optimization	• Islanded scenario was not tested • Needs testing on a more dynamic pricing scheme • BESS degradation and GHG penalty costs were not considered • Network constraints not considered
[62]	QP	2021	C	PV-WT-Battery ESS-PEV-Grid (On) [AC]	Monte-Carlo (MC) used for scenario analysis	• EMS for residential MGs comprising energy-based and comfort-based controllable loads to minimize MG costs • Thermal and electric generation combined in scheduling	• Islanding and BESS degradation were not considered • Network constraints not considered • Future work includes integrating non-interruptible loads, uncertain real-time pricing, and PEV plug-in/out times
[66]	Lagrange Multipliers	2019	C	PV-Battery ESS- Grid (On) [AC, DC coupled]	N/A*	• EMS for rooftop PV-BESS for maximizing revenue • Detailed system loss considerations. Higher revenues when compared with DP	• Islanding and BESS degradation costs were not considered • Testing should include varying local load • Computational complexity not investigated
[37]	Lagrange Multipliers	2019	C-D	Generic DG-Generic ESS-Grid (On) [AC]	N/A*	• EMS designed for a multi-MG system to maximize the profits • Mechanism for fair allocation of common line capacity between MGs	• Islanding not considered • MG inter-trading and Network constraints were not considered • BESS degradation and GHG penalty costs were not considered • Computational complexity not investigated
[67]	Lagrange Multipliers	2022	Dt	Generic sellers and buyers [Generic system]	N/A	• EMS proposed to maximize the profit of the seller and minimize the cost of the buyer using game theory with a real-time distributed algorithm	• GHG emission penalties should be incorporated
[70]	Convex	2019	H	PV-WT-Battery-Grid (On) [AC]	Adaptive Auto Regression Algorithm	• EMS to minimize the daily cost of operation, maximize self-consumption of RES and smooth the power exchange profile with the main grid • Proposed BESS control using rolling horizon and MPC control. • Operating cost reduction of 18-30% reported	• Islanding was not considered. • Network constraints need to be considered • Future work includes a testing system on real-time pricing scheme and under various faults in communication
[71]	Convex	2019	D	PV-WT-Gas/coal generators-ESS-Grid (On/Off) [AC]	N/A*	• EMS for generic MG to minimize operational costs using the sub-gradient method, where dual decomposition is used to divide the problem into sub-problems • Comprehensive study involving load classification, system outage, transmission loss, billing, and enhancing computational time performance of the EMS	• Smaller intervals for wind-speed data should be considered. • Effect of GHG penalty not considered
[72]	Convex	2019	C	PV-WT-Diesel-Microturbine-FC-BESS [AC Islanded]	N/A*	• EMS for islanded MG to minimize operational costs of MG • Significant reduction in operating cost and computational time reported, as compared to PSO and GA. Non-convex problems transformed into convex	• Smaller intervals for wind-speed data should be used. • Network constraints should be considered
[73]	Convex	2019	C	PV-Tidal turbine-diesel generator-BESS [AC Islanded]	N/A*	• EMS for islanded MG in Ouessant island (France) to minimize operational costs • Includes incentive-based DR scheme and integer-free formulation to reduce computational load. • Non-convex problem transformed into a convex problem	• Smaller time interval for the RER forecast can be considered
[74]	DP	2019	C	PV-Diesel Generator-BESS-Grid (On) [DC]	N/A*	• EMS for DC MG to minimize the cost of operation • Method proposed to reduce computational complexity/load in MG DER scheduling	• Islanding and Network constraints should be considered. • Need to consider a more dynamic pricing scheme • BESS degradation and GHG costs not considered • Computational complexity not investigated
[75]	DP	2019	C	PV-FC-BESS-Grid (On/Off) [Hybrid]	N/A*	• EMS for a magnetically coupled residential RES to minimize energy costs • DP combined with a real-time rule-based control system for scheduling • 85% reduction in cost reported, as compared to using only grid power	• Limited islanded testing (scheduling not tested) • BESS degradation costs not considered • Computational time not tested
[76]	DP + Stochastic	2020	C	PV-Gas generator-BESS [AC Islanded]	Stochastic forecast models	• EMS for islanded nano-grids to minimize fuel costs and maximize battery availability by optimizing the use of PV generation • Simplified time-variant Markov model developed for PV power generation and BESS non-linearities considered in the formulation • Savings of 19% were reported as compared to the rule-based method	• BESS degradation was not considered • Computational complexity not tested
[77]	DP	2020	C	PV-FC-BESS-Grid (On) [DC]	Grey forecast model	• EMS to minimize operational costs • Algorithm runtime and operational costs are reduced significantly by integrating MPC. 15, 20, and 30-minute rolling horizon intervals used and compared • Comparisons also made with MILP-MPC and logic-based algorithms	• Islanding not considered • Dynamic pricing schemes should be considered • Network constraints not considered
[78]	DP	2020	C	PV-WT-Micro-gas turbine-FC-ESS-Grid [AC]	N/A*	• Minimize fuel and maintenance costs in Islanded mode and minimize costs/maximize profits by trading with the grid in grid-connected mode • Multi-parameter DP method was used, considering BESS dynamic performance.	• Wind forecast needs to be on a shorter time horizon • A more dynamic pricing scheme needs to be used • Network constraints and BESS degradation were not considered
[81]	S&R + MILP	2019	C	PV-WT-Diesel Genset-Battery ESS-Grid (On/Off) [AC]	Stochastic PDF models; MC for scenario analysis	• EMS for minimization in operational cost and maximization in the comfort of households, combining heating and electric loads in scheduling • Model simulated iteratively for each 24-hour rolling horizon period for one year, considering all extreme cases in the study • Risk indices were computed to compare different cases, and sensitivity analysis was conducted to determine the effect of design parameters on decision variables. • 24% savings were reported compared to the grid-connected case without DR	• GHG penalties not considered • Computational time not considered/tested
[82]	S&R + MILP	2020	C	PV-WT-Diesel-Gensets [AC Islanded]	Stochastic PDF models; MC for scenario analysis	• EMS for islanded MG to maximize operator profits using stochastic risk-constrained scheduling. The risk associated with profit variability and DR programs incorporated • Scenarios generated using MC simulation and reduced using k-means clustering	• GHG penalties not considered • Computational times should be tested in more detail (more comparisons)
[38]	S&R + MPC	2020	H	PV-WT-Battery ESS-Grid (On) [AC Multi-MG]	Stochastic PDF and MC models	• EMS for a multi-MG cluster to minimize unexpected power exchange. • Reduction of 47% in daily unplanned power exchange with the grid achieved	• Islanding and BESS degradation were not considered • Dynamic grid prices should be considered • Computational complexity not tested. GHG penalties should be integrated with the case of fuel-powered DGs in some MGs

TABLE 4. ***(Continued.)*** **Review of microgrid EM optimization methods.**

[80]	S&R+ Fuzzy	2021	C	PV-WT-BESS-MicroCHP-Grid (On) [AC]	Stochastic PDF models	• EMS for Energy Hub to minimize the cost of operation, reduce emissions and minimize system losses, along with the reduced computational load • Uncertainty in RES, load, and grid prices handled using scenario generation. • Modified fuzzy approach was developed to reduce the optimization problem	• Islanding not considered
[40]	AIS	2015	C	Generic MG System (Only power flows considered)	N/A	• EMS for a multi-MG system to optimize revenue from the grid and each MG's consumption. • AIS helped to improve the performance of multi-objective formulation and avoid drawbacks caused by aggregate functions.	• This study may include mechanisms of intermittent renewable resources, islanding scenarios, and BESS degradation costs.
[87]	GA	2019	C	PV-Microturbine-FC-BESS-Grid (On) [AC]	Historical Data	• EMS was designed to minimize operational costs and emissions • A dynamic multi-constrained handling strategy was applied to the NSGA-II algorithm to reduce the number of constraint violations in the solutions • Comparisons made with various modified NSGA-II algorithms	• Islanding not considered • Network constraints not considered in scheduling • BESS degradation cost should be considered
[84]	GA + Fuzzy	2020	C	PV-BESS-Grid (On) [AC]	N/A*	• EMS was constructed to maximize total profit by trading with the grid • Compared to Linear programming and rolling time horizon algorithms • Performance close to 90% of the optimal performance	• Islanding and BESS degradation were not considered • A more dynamic pricing scheme should be used • Network constraints and computational time were not considered
[85]	GA	2020	C	PV-WT-Microturbine-FC-PEV-BESS-Grid (On) [AC]	N/A*	• DR integrated EMS for MG to minimize the cost of operation, consumer inconvenience, and environmental pollution, using NSGA-III • Comparisons made with R-NSGA-II. Around 30% reduction in cost reported	• Islanding and BESS degradation costs were not considered • Network constraints should be considered in scheduling • Computational time should be tested and compared
[86]	GA	2020	C	PV-Diesel generator-BESS [AC Islanded]	N/A	• EMS for islanded MG in DongAo Island to minimize operational costs • Improved GA reduces the number of infeasible solutions and shortens the time required to verify solution feasibility. At least a 40% reduction in infeasible solutions reported	• GHG penalties should be considered • Should be tested with dynamic pricing schemes • Network constraints should be considered in more detail during the scheduling
[127]	DE and Heuristic	2020	C	PV-WT-Microturbine-BESS-FC-Grid (on) [AC]	N/A*	• EMS for community-scale MG to minimize operational cost • Heuristic proposed for equality constraint satisfaction to enhance the speed of optimization algorithm	• Islanding and GHG emissions were not considered • Shorter time intervals for WT forecasting can be considered. • Network constraints not considered
[88]	GA + Fuzzy	2021	C	PV-WT-BESS-Grid (On) [DC Coupled-AC microgrid (RES and ESS on DC, loads on AC)]	N/A*	• Minimizing average peak loads and operational costs by tuning Fuzzy EMS using NSGA-II • ESS test bed used to test the real-time operational performance	• Islanding and BESS degradation were not considered • Network constraints not considered in scheduling • Computational complexity should be investigated
[128]	EA	2021	C	Grid (on) – Controllable loads [AC]	N/A*	• Evolutionary algorithm (EA) used for optimal scheduling of loads for residential customers under demand response scheme • The memetic algorithm used to accelerate the search process and to enable operation under limited computational capacity	• Islanded operation not considered • Optimization should incorporate DER scheduling as well
[129]	PSO	2019	C	PV-WT-BESS-Grid (On)	N/A*	• EMS for community MGs to minimize operational cost using modified PSO, considering BESS degradation costs • Dynamic penalty function to manage BESS charging. • 30-40% cost reduction reported	• Islanding not considered • Network constraints should be considered • Shorter forecast interval should be considered for WT • Computational complexity should be investigated
[90]	PSO	2020	Dt	PV-WT-BESS-EV-Diesel [AC/DC Hybrid Islanded]	N/A*	• EMS for minimizing operational costs, conversion losses, load shedding, and scheduling shiftable load and EV charging/discharging • An intelligent agent-based EMS proposed that accounts for AC/DC MG and system operator requirements • V2G implemented for load shifting in case of peak timings	• BESS degradation costs not considered • GHG penalty costs not considered
[91]	PSO	2020	C	PV-BESS-EV-Grid (On) [AC]	N/A*	• EMS for building MG to minimize electricity bills, reduce carbon emissions, maximize user comfort, and minimize the peak-to-average ratio • Hybrid genetic PSO proposed, which is a combination of GA and binary-PSO. Results report electricity cost reduction by 25%, peak-to-average decrease by 36%, and carbon emission reduction by 24% as compared to the case without scheduling	• Islanding and BESS degradation were not considered • Network constraints should be considered in scheduling • Computational time complexity of the method should be tested and compared
[89]	PSO	2021	H	PV-Battery ESS-EV-Grid (On/off) [DC]	N/A*	• Multi-level and multi-objective EMS proposed that include virtual battery-based droop control for multiple ESS, a decentralized coordinated control to enhance the reliability of microgrid, and current feed-forward control in the secondary level to reduce voltage deviation of the bus	• Trading with the grid should be considered in scheduling (selling not considered, only buying considered) • Network constraints not considered • Computational time complexity not tested
[98]	MILP + Heuristic	2019	C	PV-WT-Diesel-Grid (On/Off)	N/A*	• Matheuristic proposed for Emergency Order Scheduling Problem related to electric distribution operations, considering unforeseen islanding of DG • Up to 90% reduction in costs when using the proposed method as compared to no scheduling	• Smaller intervals can be considered for WT and PV forecast data for more accurate scheduling • GHG emission costs not considered • Computational complexity of the algorithm should be investigated and compared
[101]	Adjustable-Robust-MILP + Heuristic	2022	C	PV-BESS-Grid (On)	N/A*	• EMS for a residential system to minimize the cost of operation • Adaptive robust model developed that can handle uncertainties in real-time, along with using forecasted data • Matheuristics solution with MILP combined with rule-based on robust adjustment for fast decision-making solutions for short-term scheduling and real-time operation	• Islanding should be considered • BESS degradation costs not considered
[104]	Fuzzy	2020	C	PV-BESS-SC-Grid (On) [DC coupled, AC MG]	N/A*	• EMS for residential MG maximizes the grid's output power and enables optimal sharing of ESS resources. • A neuro-fuzzy Jacobi wavelet-based controller implemented in the power inverters	• Islanding not considered • Operational costs not considered • BESS degradation costs not considered • Computational time complexity not tested

TABLE 4. *(Continued.)* **Review of microgrid EM optimization methods.**

[103]	Fuzzy	2021	H	PV-WT-BESS-Flat plate collector-Water tank (Thermal ESS)-Grid (On) [AC]	Forecasting of load using persistence model and of renewables using Fuzzy model (Fuzzy model trained using past data)	• EMS for residential electro-thermal MG to minimize the import of grid power and smooth the power profile of energy exchange with the grid • 11.4% reduction in maximum power absorbed from the grid and a significant decrease in power ramp rates as compared to other methods	• Islanding not considered • BESS degradation costs not considered • Computational time complexity should be tested
[39]	Fuzzy	2021	C	PV-WT-BESS-EV-Diesel-Grid (On/Off) [AC]	Random vector functional link network (Deep NN)	• EMS for the multi-MG system to minimize consumer cost of energy consumption using peer-to-peer energy exchange algorithm with dynamic pricing • 14% cost reduction reported with the proposed strategy	• Islanding not tested • Network constraints should be considered in scheduling • BESS degradation and GHG penalty costs were not considered • Computational time complexity should be tested
[102]	Fuzzy	2022	H	PV-BESS-Hydrogen ESS-SMES [DC Islanded]	N/A*	• EMS for optimal use of ESS based on demand. • Master-slave EMS was implemented where fuzzy control is implemented at the master level to generate operational setpoints. NBF-SOSMC implemented slave-level control to regulate the power of DERs	• BESS degradation was not considered • Further testing should be conducted on 24-hour data for master-level scheduling • Computational complexity not investigated • Network constraints should be considered in scheduling
[107]	ANN	2015	C	PV-WT-BESS-EV-Grid (On)	Neural network-based, trained using Extended Kalman Filter	• EMS optimization problem was solved using a recurrent neural network, where each component was modeled as an agent in a centralized Multi-Agent system framework	• Islanded operation not considered • BESS and EV battery degradation costs were not considered • Network constraints should be considered • Computational time should be investigated
[106]	ANN	2016	C	PV-WT-BESS-Diesel Generator-Grid (On/Off)	N/A*	• Developed EMS using Action-dependent heuristic dynamic programming algorithm, which combines adaptive programming and reinforcement learning techniques • Optimization of the approach using evolutionary strategy to improve dispatch solutions over time	• A more dynamic pricing scheme can be tested. • Network constraints should be tested • Future work will include dynamic state prediction of the system and testing in a real-time environment
[105]	ANN	2017	C	PV-WT-FC-BESS-MT-Diesel Generator [DC]	Radial Basis Function Neural Network	• EMS for MG based on the Lagrange programming neural network, based on the Lagrange multiplier method, is introduced • The method was proved to be Lyapunov stable, and the stationary point of the Lagrange function is asymptotically stable • The proposed method performs significantly better as compared to PSO	• BESS degradation cost not considered (High frequency of charge-discharge cycles in this study) • Network constraints should be considered • Computational complexity should be investigated
[108]	ANN	2019	C	PV-WT-BESS-FC-MT-Grid (On)	N/A	• EMS was modeled as Markov Decision Process and solved using a deep reinforcement learning approach for real-time scheduling of an MG • Deep feedforward neural network designed to approximate optimal action-value function and deep Q-network algorithm used to train the neural network	• Islanded operation not considered • BESS degradation cost not considered • GHG emission costs should be considered • Network constraints should be considered
[110]	ANN	2020	C	BESS-FC-MT-Diesel Generator-Grid (On)	N/A	• EMS for the multi-MG system using the data-driven deep neural network without compromising user privacy • Model-free Monte Carlo reinforcement approach designed to maximize profits and reduce the peak-to-average ratio of the MG system	• Islanded operation not considered • GHG emission costs should be considered
[114]	MPC	2019	H	PV-BESS-Grid (On) [AC]	Fuzzy prediction	• EMS to minimize the cost of operation using robust MPC • Robust control system, as compared to a non-robust system, achieved reduced energy costs, enhanced power exchange profile with the grid, safer battery operation, and reduced peak loads	• Islanding not considered; BESS degradation not considered • A more dynamic pricing scheme can be tested • Transmission/network constraints not considered • Computational time complexity should be tested and compared
[116]	MPC	2020	H	PV-BESS-SC-FC-Diesel (Or Gas) Generator [DC Islanded]	N/A*	• EMS to minimize the cost of operation • Above 50% reduction in PV power curtailment and reduction in BESS dwell time at high SoC to reduce degradation • Smoother set-point variation in regenerative FC • Comparisons made with fuzzy inference method. MPC was reported to be more computationally demanding than the fuzzy inference method	• GHG penalty costs not considered • In future work, stochastic MPC methods will be considered
[111]	MPC	2021	Centralized for each MG And the decentralized MG network	PV-WT-Fossil fuel generator-BESS [AC Islanded Multi-MG]	24-hour forecast data for Optimal Day-ahead planning and 15-minute forecast data for online management using the Receding Horizon model	• EMS for the islanded multi-MG system to minimize overall operating costs and provide robustness against uncertainties of RES using Tube-MPC • A decentralized decomposition and coordination algorithm was proposed to make the EMS decentralized. • Comparisons made with the compound differential evolution algorithm, Bender's decomposition algorithm, and consensus-based algorithm	• GHG penalty costs not considered
[112]	MPC	2021	Centralized for each MG Decentralized for the network of MGs	PV-WT-BESS-Hydrogen ESS-Grid (On/Off) [AC Multi-MG]	Artificial neural network (ANN) developed with the ARIMA method	• EMS for the multi-MG system to minimize the cost of operation • Method proposed for MGs trading in a deregulated market to reduce economic losses due to deviation from the schedule. • Proposed method has been made scalable to handle the large number of constraints that will need to be handled	• Computational time complexity should be tested and compared to other methods • Network constraints should be considered during the scheduling • GHG penalty costs should be regarded as if expanding to fossil fuel-based MGs • Future work includes applying stochastic algorithms to improve the proposed method
[113]	MPC	2021	Dt	PV-WT-BESS-Hydrogen ESS-Grid (On/Off) [AC Multi-MG]	Artificial neural network (ANN) developed with the ARIMA method	• EMS for the multi-MG system to minimize the cost of operation by providing flexible services to the grid using available ESS • First level performs the Day-Ahead economic scheduling, and the second level deals with providing services to the network operator. • Distributed MPC proposed, which utilizes the interaction of MG agents to reach the optimal solution	• Computational time complexity should be compared to other methods. • Network constraints should be considered during the scheduling • GHG penalty costs should be regarded as if expanding to fossil fuel-based MGs
[115]	MPC	2021	H	PV-WT-Battery ESS-Diesel Generator-Grid (On) [AC]	Outlier-Robust Extreme Learning Machine	• EMS for the multi-MG system to minimize the cost of operation • Algorithm proposed for forecasting market electricity prices with fast computation times • Proposed forecast algorithm compared with conventional ANN and SVR. 15% reduction in cost reported using the proposed method	• Islanded operation not considered • GHG penalty costs should be considered • Network constraints should be considered in scheduling

TABLE 4. *(Continued.)* **Review of microgrid EM optimization methods.**

[118]	MAS + Fuzzy	2020	Dt	PV-WT-BESS-Grid (On)	Extreme learning machine	EMS for intelligent MG to reduce operational costs and maximize profits by trading with the grid	• Islanding not tested. BESS degradation was not considered • Network constraints not considered • Computational complexity should be investigated
[42]	MAS + Stackelberg Game Theory	2020	Dt	PV-WT-ESS-MT-Grid (On)	N/A*	• EMS for the multi-MG system to optimize energy transactions for all parties, including the individual MGs, the users, and the microgrid cluster. • Proposed system was effective and had good convergence of the solution with good reductions reported in cost.	• Islanded operation not considered. • BESS degradation cost should be considered incase of batteries. • Network constraints should be considered. • Computational complexity should be investigated
[117]	MAS	2021	Dt	PV-WT-MT-BESS-Grid (On/Off) [AC]	N/A*	• Developing secondary-level control for reactive power-sharing • Dynamic scheduling of BESS using adaptive gain SoC-triggered method Method for automatic load curtailment and restoration	• Computational complexity should be investigated
[119]	MAS	2021	Dt	PV-WT-MT-BESS-FC-Grid (On) [Hybrid]	Statistical	• EMS for the large microgrid to minimize operational costs and emissions. AC and DC combined scheduling for increased benefits. 20-40% reduction in emissions reported	• Islanding not considered • Network constraints should be considered • BESS degradation costs not considered Computational complexity should be investigated
[120]	MAS	2021	Dt	PV-WT-BESS-FC-Grid (On) [Hybrid]	Statistical	• EMS for residential MG, considering EV charging and BESS degradation costs • Agents-based scheduling for EV aggregator and load demands studied with appropriate power delivery scheme and cost uncertainty considered 5-16% increase in profits reported as compared to stochasti and uncoordinated methods	• Islanding not considered • Network constraints should be considered • Computational complexity should be investigated Future work includes adding forecasting techniques for real-time operation and expanding the proposed method to a multi-MG scenario

C – Centralized D – Decentralized Dt – Distributed H – Hierarchical S&R – Stochastic and Robust

N/A – Not Available
* – Available dataset is assumed as forecasted data

B. ACTIVE AND REACTIVE POWER

Active and Reactive power control, also called current control, is generally used in the grid-connected mode of operation or grid-following DERs in the case of islanded mode. One of the prerequisites for this type of control is a voltage reference for it to follow, which, as explained previously, is either provided by the primary grid or a grid-forming DER. Real and reactive powers can be controlled independently due to decoupled direct and quadrature reference currents, as presented in (11) and (12) [131].

$$I_{dref} = k_{pp}\left(P_{ref} - P_{calc}\right) + k_{ip}\int \left(P_{ref} - P_{calc}\right)dt \quad (11)$$

$$I_{qref} = k_{pq}\left(Q_{ref} - Q_{calc}\right) + k_{iq}\int \left(Q_{ref} - Q_{calc}\right)dt \quad (12)$$

where, P_{ref} and Q_{ref} are reference power values, and P_{calc} and Q_{calc} are calculated or actual power values. Moreover, k_{pp}, k_{pq} and k_{iq} are coefficients of the PI controller.

In [132], a direct power dynamic model for electric energy storage is proposed to control active and reactive power without employing typical inner loop current regulators. This model is implemented without a phase-locked loop, eliminating the associated time delays and instability. In [133], an active power control strategy based on the frequency bus-signaling method was proposed for an AC microgrid. The proposed system is implemented in a decentralized structure without any communication links, thus increasing the system's reliability. Ref. [134] presented a sensor-less control strategy for AC microgrids where AC voltages are measured using the virtual flux method and currents using the DC-link current. The system then utilizes these values for power control and sharing between DGs. Finally, a rule-based controller is presented in [75] to optimally control the power flows of a residential hybrid RES system according to a provided energy plan.

In [135], a multi-agent-based coordinated power and virtual inertia control were proposed for a fuel cell-based DC microgrid cluster. A power flow regulator is applied in the secondary and tertiary control layers to smoothen the connection transient process and control power flow among sub-microgrids. In [131], an optimal PI-based PQ control scheme is proposed for grid-connected microgrids, where the control parameters are tuned using PSO by targeting the minimization of error between the reference and calculated power values. Ref. [136] used the point-of-interconnection power exchange measurement to modify microgrid components' references using a closed-loop PI control scheme, aiding an open-loop dispatch function to minimize power transfer to or from the grid by increasing or decreasing the dispatchable DER outputs.

C. POWER SHARING

When several DERs are operated in parallel, there must be a mechanism through which the DERs share the load amongst themselves proportional to their ratings. This can be achieved by communication between the DERs or with central management. However, in a decentralized MG structure or when no updated setpoints are available from the EMS in a centralized MG structure, each DER must have a mechanism to compute the optimal response without communication and coordination, which is typically achieved using droop control.

An adaptive droop-based cooperative scheme is utilized in [121] to share the load by BESS installed across a PV-BESS-based DC microgrid. Ref. [137] used virtual impedance-based droop control to share the load between parallel voltage source inverters. This also eliminates the need for communication to coordinate power sharing. Aguiar et al. [138] propose an adaptive power-sharing method for fuel cells (FC) and generic ESS for DC microgrids based on the k-sharing method. The k-sharing method exhibits high levels of stability and minimum disruptions at the FC-terminals. A fuzzy adaptive compensation control is presented in [139] for managing the disproportional reactive power sharing that can arise due to mismatched impedances of the distributed generation. The controller achieves this by varying the voltage reference signal of the DERs in real-time.

Ref. [140] focuses on superimposed frequency droop control for power sharing in DC microgrids. The paper formulated two parameters to improve the stability and loading issues of such a method: the adaptive voltage coupling gain and adaptive amplitude of the injected AC voltage. Control of these parameters improved the system operation under different loading conditions.

In [141], a secondary control system was implemented for frequency restoration and active power sharing using a non-linear, bounded controller formulated with Lipchitz continuity dynamic function. Ref. [142] focuses on islanded microgrids, where a decentralized direct current primary controller was presented for accurate proportional active power sharing and frequency deviation, which performed better than a conventional droop controller. Moreover, a distributed consensus-based quadrature controller is implemented for reactive power sharing under mismatched feeder impedances, employing minimal communication. Peyghami et al. [143] work on improving the reliability of DC microgrid operation by distributing thermal stresses on DC converters proportionately among them. According to the proposed strategy, the higher the thermal stress on a converter, the lower its power supply. In [144], a distributed power flow regulator for power sharing among DERs was proposed in the secondary control layer. Additionally, this control ensures power and voltage regulation of each phase. In [130] and [145], a distributed control is implemented in an islanded microgrid with the objective of optimal power control. This is accomplished by using droop control combined with a MAS secondary controller to manage deviations of setpoints. Ref. [146] proposed an event-triggered communication protocol-based reactive power-sharing approach with the consensus principle for MGs. A MAS-based ring network was established to form the communication between DGs, which aims to reduce the communication between neighboring DGs, thus saving resources and enhancing system reliability.

D. TRANSITION CONTROL

Transition control mainly involves transferring MG operation from grid-connected to islanded and vice versa. Effective transition is essential because the MG parameters, such as voltage and frequency, should not deviate from the safe operating range to avoid instability. The main reason for disturbance during transition is the control mechanism change, such as the transfer from voltage control to current control.

This section reviews methods used in the literature to maintain the stability of MG parameters during transition events. Zheng et al. [147] present a smooth transition control scheme for ESS to operate in grid-connected and islanded modes. A combination of MPC and a two-degree-of-freedom control algorithm is implemented as a single control structure to promote a smooth transition between modes, which can alleviate control disturbances by adopting a control structure that appears as unity power gain. Ref. [148] presents a dual-stage cascaded operational control for a seamless microgrid transition from islanded to grid-connected. The first stage utilizes a bi-directional converter to match and equalize parameters between the microgrid and the grid using a prefiltering moving average filter and an adaptive proportional-integral controller. Next, a transition controller bypasses the converter and connects the microgrid to the main grid using a bypass switch. In [149], the performance of the H∞ controller and MPC controller is compared for a seamless transition between islanded and grid-connected modes of microgrid operation. It was reported that the H∞ controller performed better according to the following metrics: integral of square error (ISE), integral of absolute error (IAE), and integral time-weighted absolute error (ITAE).

The authors of [136] present a transition function for AC microgrid using state-saving techniques, active synchronization, and emergency dispatch, with ESS as the main facilitator to provide a smooth profile. Moreover, a transient virtual resistor control is adopted for improved dynamic performance. In [150], a cascaded control strategy enables smooth state transition within a single control structure, allowing the controller to be independent of mode switching. Ref. [151] presents a linear voltage controller with capacitor current feedback as an input to the voltage controller and output current feedforward as an input to the current controller, and a modified droop control to emulate the inertia response of a synchronous generator, which can suppress voltage, current, and frequency fluctuations as well as provide a smooth transition.

In [152], a simple mixed droop-v/f control strategy is proposed for the master inverter to achieve seamless mode transfer for a master-slave microgrid between grid-connected and islanding modes. To facilitate the seamless transfer from grid-connected to islanding mode, a modified droop control strategy, which is effective for accurate reactive power regulation, is adopted in grid-connected mode. On the other hand, V/F control, which is realized by reducing the droop coefficient gradually to zero after islanding, is adopted in islanding mode. In addition, pre-synchronization between the microgrid and utility grid, achieved using a Phase-Locked-Loop (PLL), is used to reconnect them seamlessly. Finally, A review paper is presented by [153] regarding implementing MG control strategies to enable a smooth transition between grid-connected and islanded operation modes, where current challenges and articles addressing them are outlined. Table 5 summarizes the microgrid control methods.

V. IEEE STANDARDS FOR MICROGRID EMCS

Standards provide a verified and accepted set of rules to follow in industry and research. They can guide researchers to work within a common framework and compare new research methodologies with standardized benchmark systems on parameters outlined in the various standards. EMCS research has also undergone considerable standardization, ranging from interconnection and interoperability guides to microgrid controllers and DERMS standardization. This section reviews the papers in the literature that have used various IEEE standards related to EMCS in their work.

A. IEEE STD. 1547: STANDARD FOR INTERCONNECTING DISTRIBUTED RESOURCES WITH ELECTRIC POWER SYSTEMS

The focus of this standard is to provide the technical specifications and testing requirements for the interconnection and interoperability between utility electric power systems (EPSs) and DERs with a maximum aggregate capacity of 10 MVA [154]. This provides the generalized standard for ensuring interoperability in various technical aspects of DER connection to the grid at the primary or secondary networks of the grid. Whereas it is not exclusively made for microgrids, this has been followed extensively in the literature for microgrids, which predominantly utilize distributed generation. The microgrid transition issue is one of the topics covered in this standard and has been implemented in [155], [156], [157]. Wang et al. [155] implement the transition operation logic based on recommendations of this standard and realize automatic and smooth transitions among all the states of microgrid operation. An algorithm in real-time simulation hardware is developed in [156] to test a microgrid's planned and unplanned islanding, keeping the frequency and voltage limits in view.

The IEEE Std. 1547 is used in [157] to design control for islanding the microgrid whenever specified disturbances, such as faults or power quality events, are detected in the main grid. Moreover, a reverse power test is also carried out based on Test 6.1.2, which specifies requirements for islanding when the microgrid loses the utility source so that there is no reverse power flow to the transmission or adjacent distribution networks. Eliminating reverse power is crucial to ensure the safety of maintenance personnel. The 1547 standard also outlines the limits for voltage and frequency regulation for 60Hz grids, which have been observed in [126], [156], [158], [159]. Ref. [126] studies the maintenance of the voltage and frequency of a microgrid within limits during a grid resynchronization event. On the other hand, Ref. [149] proposes a control strategy to achieve frequency and voltage regulation in IEEE1547 limits by controlling thermostatically controlled loads in a community microgrid while maintaining customer comfort levels. Ross et al. [159] propose V/F control for ESS to maintain the microgrid voltage and frequency.

The ride-through capability requirements of DERs under voltage and frequency deviation have been specified in detail in the 2018 version of the standard. Three categories of ride-through characteristics have been defined that can be applied to DERs based on various technologies or DER penetration levels. In [160], the effect of transmission level faults in the U.S. Western Interconnection on inverter-interfaced DERs in the distribution level is assessed, and their ability to ride through voltage deviations is based on said categories defined in IEEE 1547. It is found that DER characteristics are crucial to the recovery of power systems immediately following faults. Thus, it is essential to study the operational characteristics of inverter-based DERs during system transients and develop more accurate models to represent this behavior. To this end, the study in [161] explored the general fault response of DERs that follow IEEE 1547-2018. Additionally, an inverter model that complies with the standard is simulated and tested to compare with off-the-shelf inverter models for fault response.

In [162], the performance of different detection methods for single-phase inverters during abnormal transients was compared to the IEEE 1547 standard for ride-through and intentional islanding scenarios. In addition to simulations, the model is also implemented in a Field Programmable Gate Array (FPGA)-based controller hardware-in-the-loop set-up and assessed for steady-state and transient performance. In [163], PV inverter compliance with the IEEE 1547 phase-angle change ride-through (PCRT) test sequence is tested under unbalanced and balanced phase-jump conditions and compared to inverters that were not compliant with the standard. Distorted grid voltages could cause miscalculations in PLL modules that may lead to pre-mature islanding of the DER. However, the study helped provide insight into their performance when subjected to phase jump changes and to identify potential improvements that can be implemented to increase reliability.

B. IEEE STD. 1547.3: GUIDE FOR MONITORING, INFORMATION EXCHANGE, AND CONTROL OF DISTRIBUTED RESOURCES INTERCONNECTED WITH ELECTRIC POWER SYSTEMS

This guide is intended to facilitate the interoperability of DERs and help DER project stakeholders implement monitoring, information exchange, and control (MIC) to support the technical and business operations of DR and transactions among the stakeholders [164]. In [165], the authors present the Distributed Network Protocol (DNP) for microgrid communication under the IEEE 1547.3 requirements for data exchange, performance, and security. The authors discussed the communication network infrastructure, the interoperability and availability of infrastructure, communication delivery time performance, open communication architecture, and communication protocols, all of which are part of the 1547.3 standards. In [166], these guidelines are followed to establish communication between the DER stakeholders (who own the DERs) and the area electric power system operator (AEPSO), DER aggregator, DER maintainer, and DER operator.

Ref. [167] uses this standard for performance analysis of peer-to-peer architecture in microgrid trading systems. The results from the paper are analyzed, including peer discovery and message delivery using latency, bandwidth cost (throughput), and reliability as performance metrics, which are part of the standard. A real-time test bed is presented in [168] for multiagent system interoperability based on the 1547.3 standards, where the agents are categorized

TABLE 5. Review of microgrid control methods.

Ref.	Control Type	Year	Main Objective	Other controls used	MG Control Structure	Microgrid Type	Other Remarks
[130]	Voltage and Frequency	2019	Conventional droop for primary control for voltage and frequency control, and multi-agent system-based secondary control to eliminate voltage and frequency deviations from rated values in inverter-based DGs	• Active and reactive power regulators in secondary control of DGs • Dual-loop controller for current and voltage regulation	Dt	AC	• Proposed method tested against variable communication structures during disconnections • Proposed strategy requires minimal communication
[121]	Voltage	2020	Nonlinear cooperative strategy used for BESS SoC balancing and voltage regulation in primary control. Secondary control also implemented to account for MG voltage drift due to communication delay	• MPPT and Voltage Droop control for PV	Dt	DC Islanded	• BESS degradation was catered for by using constant voltage charging such that BESS current starts reducing to zero at high SoC • State-space model established for MG under time delay • Hardware validation conducted
[124]	Voltage	2020	Outer supervisory control of PV and BESS control bus voltage using nonlinear adaptive droop controller based on optimal profiles for speed of charge/discharge	• Inner control loop of BESS and PV uses the PI current controller	D	DC Islanded	• Proposed system maximized the use of MPPT control, enhanced the dynamic response of the system against transients, and regulated bus voltage • Voltage deviation under full load reduced from 20V to 6V using the proposed method as compared to conventional droop controller • Hardware validation conducted
[125]	Voltage	2020	Fractional Order PID controller used for bus voltage regulation	• Speed MPPT controller for WT • Single input fuzzy logic-based MPPT for PV. • PI controller for AC load voltage regulation and Hydrogen ESS	D	DC Islanded	• Hardware validation conducted
[126]	Voltage	2020	Proportional Resonance controller used for voltage regulation and PI controller for DC-link voltage of PV-BESS system	• Incremental conductance MPPT for PV • Neural filter-based current control for voltage source AC/DC converter	D	AC	• Seamless transition between current control and voltage control for grid-connected mode and islanded mode, respectively • 3% THD reported with the proposed method • Hardware validation conducted
[122]	Voltage	2021	Type II controller with k-factor approach used for BESS and a lookup table based-nonlinear PI control is used for SC to regulate MG voltage	• Benchmark low-pass filter-based controller applied to ESS for comparison • Perturb and observe MPPT for PV	C	DC Islanded	• Voltage regulation improved by 4% in case of deficient power and 7% in case of excess power, as compared to low pass filter-based controller • A BESS and SC combined system was formulated to tackle high and low-frequency power variations
[123]	Voltage	2021	Droop control modified with voltage shifting technique used for voltage regulation of MG	• Load sharing was achieved using master-slave control where the master superimposes AC signal on DC bus voltage for DG frequency droop controller	D	DC	• Proposed system provides the plug-and-play capability and seamless transition between grid-connected and islanded modes of operation. • Hardware validation conducted
[132]	Active and Reactive Power	2019	PI passivity-based control for instantaneous power control of SMES and SC, without the use of inner loop current regulator and PLL	-	D	AC	• Elimination of PLL reduced multipliers and states in the system model • Model exhibits port Hamiltonian structure in an open loop with the use of PI passivity-based control while also guaranteeing global asymptotic stability in closed-loop
[133]	Active Power	2019	Communication-less frequency recovery method proposed for frequency bus-signaling method in MG using PV and BESS power controllers	• Voltage and current regulation for BESS and PV • Perturb and observe MPPT for PV	D	AC Islanded	• Reduced cost of the system, system extensibility improved • BESS protection against over-charging/discharging considered
[134]	Active and Reactive Power	2019	Method of droop control without using AC sensors in inverters, using only DC link voltage and current and estimating AC values	• Voltage and current regulation for inverters	D	AC Islanded	• Virtual flux-based voltage reconstruction method developed • Hardware volume and cost reduced • Hardware validation conducted
[135]	Active Power	2019	MAS-based power control with virtual inertia for FC	• MPPT-Virtual inertia control for PV • Droop control for BESS • Voltage regulation of MG cluster using MAS	D-Dt	DC Cluster	• Exhibits plug and play capability, bus voltage smooth control, SoC consistency control, and effective load abrupt response • Hardware validation conducted
[131]	Active and Reactive Power	2019	PSO was used to optimize parameters for current control in inverters, aiming at minimizing settling time after disturbance	• Dual loop controller for current and voltage regulation in inverters	D	AC	• Proposed method optimizes current controller parameters and filter parameters to optimize the system response • Hardware validation conducted
[136]	Active and Reactive Power	2020	Slack bus power control strategy proposed	• Voltage-frequency control in islanded mode • Droop control for diesel generator. • MPPT control for PV and WT	C	AC	• Rule-based power dispatch proposed with ESS power smoothing and force charge/discharge control • Smooth transition control implemented • Hardware validation conducted
[141]	Power Sharing	2019	MAS-based secondary control for power sharing and voltage frequency in MG	• Power droop controller in DC inverters • Voltage and current control in DG inverter	Dt	AC Islanded	• Nonlinear dynamic beta cumulative distribution function introduced for accelerating convergence speed of secondary control, ensuring asymptotical convergence of secondary control and diminishing transient overshoot as compared with traditional secondary control
[143]	Power Sharing	2019	Improved droop control for reliable power sharing control strategy to evenly distribute thermal stresses among DGs to improve converter lifetime and reduce downtime due to maintenance	• Current and voltage controller for PV, FC, and BESS • Perturb and observe the MPPT algorithm for PV	C or Dt	DC	• Proposed approach learns from historical data to evaluate the damage to components and adjusts power output accordingly • System reliability increased by 16% using the proposed method as compared to the conventional power-sharing approach • Hardware validation conducted
[137]	Power Sharing	2020	Virtual impedance-based droop control proposed for power sharing among DGs	• Dual loop controller for current and voltage regulation in inverters	D	AC Islanded	• Transient performance improved significantly • Reduced hardware cost of the system • Hardware validation conducted
[138]	Power Sharing	2020	Adaptive k-sharing method proposed for FC-BESS system where BESS manages faster transients and FC supplied low-frequency variations	• DC link voltage controller • FC and BESS's current controller	C	DC	• DC voltage error reduced by 1.4% • Hardware validation conducted
[139]	Power Sharing	2020	Power sharing was based on frequency droop control. Fuzzy adaptive compensation method proposed for accurate reactive power sharing in MG to cater to imbalances arising from mismatched impedances of DGs and unbalanced loads	• Dual loop controller for current and voltage regulation in inverters	C	AC Islanded	• Fuzzy controller modifies the reference voltage value to achieve effective sharing of reactive power • Method uses low bandwidth communication • Hardware validation conducted
[140]	Power Sharing	2021	Improved frequency droop method for power sharing utilizing adaptive voltage coupling gain and amplitude of injected AC voltage	• Dual loop controller for current and voltage regulation in DGs	D	DC Islanded	• Enhances voltage quality and increases maximum system loading • Hardware validation conducted
[142]	Power Sharing	2021	Decentralized direct current primary controller and distributed consensus-based quadrature current controller proposed for power-sharing	• PR voltage controller and proportional current controller for DG inverters	D-Dt	AC Islanded	• Proposed method provides faster transient response and accurate power sharing under minimum communication requirements • Effect of communication delays and failures evaluated • Frequency deviation of less than 40 mHz was reported, and power-sharing achieved in less than 2 seconds • Hardware validation conducted

TABLE 5. *(Continued.)* **Review of microgrid control methods.**

[144]	Power Sharing	2021	Distributed secondary power flow regulator proposed for power sharing control among DGs and phases	• Distributed secondary voltage regulator implemented in DGs for voltage restoration and power quality improvement • Phase independent-virtual synchronous generator control proposed for independent power and voltage control in primary control of DGs	Dt	AC Islanded	• Effect of communication delays was considered • Proposed method improved the unbalance of power in a three-phase system, and each phase becomes more stable and resilient to load changes
[147]	Transition	2019	Strategies proposed for a seamless transition between grid-connected and islanded operation utilizing BESS and DG inverter control	• Voltage and current controllers in DG inverter	D	AC	• MPC and two-degree freedom control combined into a single structure for inverter current control • Voltage and angular frequency feedforward compensation for PQ and modified droop control reduce MG fluctuations. • Planned and non-planned islanding considered
[152]	Transition	2019	Proposed method combines modified droop control and VF control, where the droop coefficient is reduced to zero in islanded mode	• Current and voltage regulation in inverter	D	AC	• Voltage synchronized within 250ms • Hardware validation conducted
[148]	Transition	2020	Dynamic reference frequency loop-based resynchronization controller proposed to control a bi-directional controller used for transition control of MG from islanded to grid-connected	• PQ controller for grid-following mode and VF control for islanded mode implemented in inverter	D	AC	• Proposed method is two-staged, where the first stage equalizer parameters of MG with the grid by building up MG parameters to equal normal grid-connected operation, and the second stage operates the reconnection switch • Proposed method uses a bi-directional converter to converter to attain smooth resynchronization without affecting the MG stability • Time taken for resynchronization is less than 1 second, as compared to 5-20 seconds for other methods in the literature
[149]	Transition	2020	MPC and H∞ droop control proposed for voltage source inverters and compared for islanded and grid-connected operation and transition	• MPC controller proposed to improve the behavior of droop control in Islanded mode of operation • PQ control for grid-connected operation.	D	AC	• Proposed methods provide a seamless transition and improve voltage and frequency waveforms and reduce deviations • H∞ control performed 17-50% better in performance indices for load voltage and frequency as compared to MPC
[150]	Transition	2020	MG transitions handled using applying cascaded control; strategy using a single control structure, and interfacing Non-linear Simplex based algorithm with EMT simulations to search for optimal controller parameters	• PQ controller for grid-following mode and VF control for islanded mode implemented in inverter	D	AC	• Significant improvements reported for voltage and frequency fluctuations as well as total harmonic distortion • Hardware validation conducted
[151]	Transition	2020	Proposed method includes a modified droop controller and linear voltage controller with capacitor current feedback input to the voltage controller and outputs current feedforward as an input to the current controller	• Power control for grid-connected operation	D	AC	• Proposed strategy provides more damping and better transient performance • Overshoot of output current reduced from 200% to 5%. • Hardware validation conducted

C – Centralized D – Decentralized Dt – Distributed

into AEPSO, microgrid, and DER agents in a hierarchical structure.

C. IEEE STD. 1547.6: RECOMMENDED PRACTICE FOR INTERCONNECTING DISTRIBUTED RESOURCES WITH ELECTRIC POWER SYSTEMS DISTRIBUTION SECONDARY NETWORKS

This standard provides recommendations and guidance for DER interconnection on distribution secondary networks (DSN), including spot and grid networks. IEEE Std 1547.6 was specifically developed to provide additional information regarding interconnecting DER with DSN [169]. This is especially relevant because most microgrids are designed at the distribution level.

An algorithm is proposed in [170] for intentionally islanding loads in low-voltage DC distribution systems. This island can be a single or multiple sub-islands. The test system used in this paper is taken from the IEEE Std. 1547.6. Ref. [171] presents microgrid structures as building blocks for active distribution networks. Here, a dynamic system refers to an isolated portion of a distribution system with DGs, e.g., an islanded secondary network with DGs. As the standard recommends, one should not cause any network protection device to separate or connect two dynamic systems.

This paper [172] proposed a resilience-oriented method to determine restoration strategies for secondary network distribution systems after a major disaster. Technical issues associated with the restoration process are analyzed, including the operation of network protectors, inrush currents caused by the energization of network transformers, synchronization of DGs to the network, and circulating currents among DGs. A look-ahead load restoration framework is proposed, incorporating technical issues associated with secondary networks, DG capacity and generation resources limits, dynamic constraints, and operational limits. Moreover, it is mentioned in the standard that the aggregate capacity of the DERs should be less than 50 percent of the local electric power system to improve grid reliability, which the authors of [164] observe in their work for optimally locating solar PV in the distribution network.

D. IEEE STD. 2030: GUIDE FOR CONTROL AND AUTOMATION INSTALLATIONS APPLIED TO THE ELECTRIC POWER INFRASTRUCTURE

This standard outlines the best practices and alternative approaches for achieving smart grid interoperability. It is the first all-encompassing IEEE standard on smart grid interoperability and is based on technical disciplines in power applications and information exchange and control through communications. The IEEE 2030 Smart Grid Interoperability Reference Model (SGIRM) defines three integrated architectural perspectives: power systems, communications technology, and information technology. Additionally, it defines design tables and the classification of data flow characteristics necessary for interoperability [173].

Ref. [174] describes an offline co-simulation testbed for smart grids based on IEEE Std. 2030 which is developed by integrating well-established power and communication systems simulators. The testbed development approach, setup, and implementation are described at a detailed level to enable similar test-bed developments. The developed testbed is envisioned to help smart grid researchers study relevant research problems, such as assessing power system resilience against cyber-attacks and threats and verifying the performance of cyber-enabled control schemes. To address the high amounts of data to be handled in smart grid applications, ref. [175] presents a big data eco-system based on Lambda architecture for operations on smart grid data.

In [176], communication strategies are discussed, and a unified communication strategy is proposed to improve the efficiency of smart grids. The paper considers various requirements outlined in the 2030 standard, such as communication latency, delay, quality of service, and reliability in application areas ranging from generation to distribution. The 2030 standard classifies customer premises networks as home area networks, business area networks, and industrial area networks. Ref. [177] investigates the optimal profile for communication technologies for smart grid networks based on these network classifications. This paper [178] works on risk-averse transmission path selection to improve data communication's reliability and resiliency in Advanced metering infrastructure (AMI) applications for smart grids. Finally, in [179], a communication interface for end-use applications outlined in the 2030 standard is used in a hierarchical multi-agent management system for EV integration with the grid.

E. IEEE STD. 2030.6: IEEE APPROVED DRAFT GUIDE FOR THE BENEFIT EVALUATION OF ELECTRIC POWER GRID CUSTOMER DEMAND RESPONSE

This standard provides a guide for Demand response applications in smart grids. The standard establishes the effect monitoring index system of DR programs and proposes the methods for DR baseline calculation and comprehensive benefit evaluation. According to the different DR program types from the perspective of different market entities, the proposed methods can perform corresponding comprehensive system analysis of the benefits and provide regulation and guidance to the projects under various market structures [180].

Ref. [181] designs an energy-sharing framework with combined heat and power generation (CHP) and an integrated DR program where prosumers' electrical and thermal loads are controlled to reduce system operating costs based on coalition game optimization. Ref. [182] utilizes mixed integer programming to schedule load using a DR program to prolong the running time of an isolated microgrid in case of emergencies by saving total fuel consumption. In [183], demand side management is developed and tested on one year of experience in South Korea's DR program. The financial savings and energy conservation for the proposed method are discussed.

F. IEEE STD 2030.7: IEEE STANDARD FOR THE SPECIFICATION OF MICROGRID CONTROLLERS

This standard addresses the need for a single technical standard for microgrid controllers to avoid negative impacts on the microgrid system by providing uniform criteria and requirements relevant to the performance and operation of the microgrid controller at the point of the interconnection. This standard intends to define the functional requirements of the microgrid controller in a manner that can be universally adopted. The two core functions for a microgrid controller, as required by IEEE2030.7, are: 1) The dispatch function, which defines the set-points of DER and controllable loads in grid-connected and islanded modes, and 2) The transition function, which defines the controller operation in transition from grid-connected and islanded mode and reconnection [184].

Razeghi et al. [185] developed and tested specifications for a generic microgrid controller (GMC) based on the 2030.7 standards. The controller is tested on a 20MW community microgrid and a 10MW hospital microgrid. Both transition and dispatch functions are implemented and tested in a real-time environment for verification. Ref. [186] adds further work by developing microgrid self-healing capabilities into the controller for the islanded operation to improve reliability and resiliency to supply critical loads within the microgrid. The work is tested in MATLAB simulation on the University of California-Irvine microgrid system. Lee et al. [187] work on developing substation control for microgrids based on the GMC and show that substation automation and control can increase renewable penetration and reduce emissions without any necessary upgrades to the grid infrastructure.

In [188], an EM strategy is developed for DC microgrids and compared to power management strategies adopted in the 2030.7 standards based on voltage sustainability, utilization factor, and average current of BESS. Ref. [189] presents a decision tree-based dispatch strategy for microgrid dispatch function to provide a solution for practical PLC-based microgrid controllers that usually use rule-based systems, where it is challenging to implement MILP optimization. Ref. [190] is a project report by Argonne National Laboratories, where an EM system is implemented for the AC microgrid. The 2030.7 standard requirement for microgrid connection/disconnection (and transitions) at the point of interconnection has been successfully fulfilled in this project. Ref. [191] investigates the viability of the IEC 61850 generic object-oriented substation event protocol (GOOSE) based control strategy for managing the transition of a microgrid test system from grid connected to the islanded mode of operation.

G. IEEE STD. 2030.8: STANDARD FOR THE TESTING OF MICROGRID CONTROLLERS

This standard provides the testing requirements for microgrid controllers by defining uniform initial conditions, initiating events, measurement criteria, and requirements relevant to the performance and operation of the MG being controlled at the point of the interconnection. This standard intends to define the initial test conditions, initiation events, and testing needed to characterize and validate the controller operations and functionality of the microgrid controller in a manner that can be universally adopted [192].

Testing two MG applications is the focus of this standard, namely dispatch and transition control. The power system disturbances are outlined for dispatch control, including open and short circuit conditions. Other testing includes the stable operation following the tripping of DERs, DER setpoint change, and start/stop of the largest load in the microgrid. Moreover, performance requirements under the operation of voltage control devices and PQ load change to maximum/minimum limits of the DERs are also mentioned. For transition testing, considerations include stable operation under both planned and unplanned islanding, request for black-start operation, and successful reconnection following islanding.

VI. DISCUSSION AND RECOMMENDATIONS

A microgrid comprises different types of DERs, with varying power outputs and availability factors. This can cause faster dynamics in operation as compared to large and centralized generations. An EMCS is thus very crucial for the stable operation of a microgrid. This review observed that many microgrid EMCS articles were published in the past two decades. The research work and emphasis in literature have generally shifted from theoretical and simulation modeling to practical implementations and actual case studies, with many projects completed worldwide [193]. It has been observed that despite numerous methods and strategies proposed in this research area, some aspects have not yet received enough consideration and still need more attention and in-depth studies. This section provides a general discussion of EM optimization and real-time control with specific recommendations.

Firstly, with the increasing use of RES in the power grid and the predominant use of RES in MG research, it would be more reasonable to use shorter intervals in forecasting and optimization computations. This is owing to the fact that, due to the intermittent nature of wind and solar PV, the forecast could change considerably within a matter of a few minutes. The majority of the papers used intervals of 1hr. and 24hrs. It is, therefore, recommended that this should be reduced to intervals of 5-15 mins. Moreover, many countries are adopting more dynamic pricing schemes, such as real-time pricing (RTP), which are more suited to trading energy from the intermittent RES. This further entails that shorter forecast and computation intervals should be used for optimization.

With an increasing need for smaller computation intervals, an expanding number of functions required of smart microgrids, and vastly varying DERs being considered for microgrids, there is a need to design more efficient EMCS algorithms that require lower computational capacity. In this study, it was noticed that not many papers have considered analyzing computational complexity and or compared performance with other existing algorithms. Therefore, there is a need for factoring in computational complexity and comparing various parameters with other proposed methods in the literature to enable a more concerted and productive effort at incrementing the microgrid EMCS research. This will further help the industry save on expenses related to upgrading computational capacities.

Microgrids range from small home and building-level MGs to large campus and district-level MGs. The various sizes of microgrids require different strategies to enable efficient and stable operation. Firstly, when considering EMCS structures, centralized systems are more suited to small-sized microgrids. This is because the communication lines are shorter, the number of DERs is small and thus requires lower computational capacity, and chances of expansion in the future are small. On the other hand, decentralized and distributed EMCS structures are more suited to medium/large-sized microgrids since they can better facilitate the system's expansion. Moreover, decentralized and distributed systems reduce the risk of cyber-attacks on a single EMCS point, thus reducing the risk of total system failure. This is an increasingly critical aspect to consider as systems become more interconnected. Secondly, network constraints must be considered when scheduling DERs in large microgrids due to the relatively wider spread of the power grid and the larger amount of electric power involved. However, this is not a pressing concern in smaller microgrids and can be disregarded to simplify the problem formulation.

The current review of real-time control methods shows that most of the methods are decentralized. This is perhaps because most control systems are implemented within the DERs. Moreover, while most of the research is done on AC systems, the trend in research on DC control systems is increasing. The study topics in microgrid control systems included improving performance under communication delays, providing a faster and more stable transient response, reducing control structure complexity for smoother and faster response, and managing BESS charge/discharge to minimize degradation. Also, numerous papers tested their proposed control methods on hardware setups and compared results with software simulation for better validation.

In the review of papers following IEEE standards on microgrid EMCS, many articles followed voltage and frequency deviation limits from IEEE 1547 series. Moreover, rules related to communication included testing various protocols for EMCS, such as DNP and peer-to-peer communication, and testing the proposed systems based on parameters such as latency, bandwidth cost, and communication reliability. The IEEE 2030 series tackled smart grid interoperability topics, ranging from communication and data handling for AMI, EV integration, and demand response, among other applications. Finally, design and testing guides for microgrid controllers include dispatch and transition control and their testing requirements.

In general, further recommendations regarding EMCS research in microgrids are summarized as follows:

- Islanding should always be considered and tested with proposed strategies because the ability to isolate constitutes the main feature of microgrids.

- BESS degradation costs should be considered in optimization problem formulation, as this will help in scheduling to prolong BESS life, which is an expensive investment in microgrids.
- Effect of communication failures with proposed algorithms should be investigated in detail, and strategies devised to ensure system stability and availability in such situations.
- RES and market price prediction intervals should be short (5-15 mins).
- If islanded microgrids are being considered, fuel-based generators should be installed for emergency backup.

VII. CONCLUSION

The need for grid expansion and renewable energy resources integration is inevitable and hence increasing around the globe due to the ever-growing population. This brings numerous challenges, including the need for considerable investments in transmission lines and issues related to cascading blackouts. In view of the mentioned issues, microgrids prove to be a promising alternative method of grid restructuring to cater to the future demand of grid expansion and transformation needs. However, due to the distributed nature of its resources, microgrids need complex energy management and control systems to operate in a stable and cost-effective manner. This area still attracts interest despite publishing many papers in the past decade. This paper has critically reviewed recently published EMCS methods in microgrids.

Microgrid fundamentals are first discussed to provide a general overview of the field, with forecasting methods and communication strategies discussed. Various DERs have been covered in the reviewed literature, including solar PV, wind turbines, fuel-based generators, ESS, and fuel cells. Based on microgrid operation, proposed methods have been classified as grid-connected and islanded. Next, a literature review was conducted on the various classical and intelligent methods proposed for energy management optimization and control methods in microgrid applications. The papers considered several objective functions, including minimization of energy storage degradation, operational costs and carbon footprint of the microgrid, or maximization of profits by trading with the grid. The review of real-time control methods was considered from an application perspective and included publications on voltage-frequency, active-reactive power, power sharing, and transition control.

Finally, IEEE standards related to microgrid operation and control are considered, and papers in literature following the standards are also reviewed, with topics related to technical parameter limits, communication protocols, and microgrid controllers covered. This will help the power system researchers build upon a standardized set of rules and aid future interoperability of the proposed methods in EMCS. The protection coordination strategies and cybersecurity issues for microgrids can be investigated in the future as an extension of this study.

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