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SURVEY

Decentralized, Democratized, and Decarbonized Future Electric Power Distribution Grids: A Survey on the Paradigm Shift From the Conventional Power System to Micro Grid Structures

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ABSTRACT Micro-Grid (MG), a paradigm shift in conventional distribution power systems, facilitates the integration of many Renewable Energy Resources (RERs), storage units, and loads. The key catalyst behind this emerging paradigm is the increased attention to environment-energy sustainability nexus. This novel concept exhibits various attractive features such as sustainability, reliability, resilience, improved power quality, energy security, and liberalization of electric service industries. However, the integration of RER units and load participation into the MG brings various challenges to the stability and operation of the system. These challenges arise as a consequence of the intermittent nature of RERs due to their stochastic behavior and increased level of non-linearity associated with smart load participation. Furthermore, in recent years, the development and deployment of RER in MG networks have demonstrated exponential growth. Therefore, in order to achieve a holistic analysis, a comprehensive review study about various aspects of MG should be investigated. In this regard, this rigorous survey paper presents the meticulous study of various aspects, historical evolution, and key enabling yet transdisciplinary technologies of MG, such as various components, generation resources, load classification, communication infrastructure, energy management, control and optimization, operational modes, and various frameworks, configurations, architectures, and topologies-including the emerging concept of Networked MG with flexible boundaries. This study also reviewed various storage and protection systems in MG, considering the attention to their contributions to the stability of the system. This review also underscores many key issues, challenges, and factors related to the sustainable development of the MG system. Lastly, an all-inclusive cross-sectoral analysis that includes cyber-physical systems, power quality, information and data management, conversion systems, synthetic inertia, and some governance issues has been provided, along with the future directions, progression, and latest development in the field of MG. This survey, therefore, greatly assists and enables researchers to study and analyze the development and prospect of MG technology conveniently.

INDEX TERMS Micro-grid architectures, communications technology, load classification, power generation resources, storage technology.

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I. INTRODUCTION

The most novel aspect of modern power networks is the deployment of Renewable Energy Resources (RERs) in parallel with conventional electricity generation and local load in small interconnected systems, i.e., Micro-Grid (MG). The advantages of this transformation at a small scale include expandability, efficiency, reliability, and economic benefits [1]. In addition to the abovementioned advantages an attractive feature of this localized system is its ability to operate both in autonomous and grid-connected modes. These benefits, in turn, bring three Ds concepts in the world's electricity systems, i.e., Decentralization, Democratization, and Decarbonization of energy, mainly following the bottom-up integration approach for Distributed Energy Resources (DERs). In the United States, the key driver for MG deployment was to enhance the resiliency and reliability of the grid, while in Europe, climate change and large-scale integration are two significant factors of MG development [2]. In order to reduce the anthropogenic carbon emissions released by burning fossil fuels for electricity generation, climate scientists have concluded that the current level of around 60-70% fossil fuels dependence must be reduced to under 20% to keep the rising temperature below 2 degrees Celsius [5]. Various DERs and RERs to counterbalance the energy supply and demand are non-dispatchable, distributed, decentralized, and intermittent. Thus, the key driving factor behind this paradigm shift is energy- environment- security nexus, and figure 1 illustrates these factors in detail [2].

Moreover, the integration of DERs in the conventional electrical grid to fulfill the environment-energy nexus requirements is complex to manage and control. However, the deployment and inclusion of the aforementioned energy resources locally with smart/flexible load and storage systems in the form of MG is the most appropriate and viable solution. This MG appears to the power utility at the distribution level as a collective entity of small-scale sources and consumers, hence, can operate in ways to modify the net load profiles easily in comparison to tracking and coordinating every DERs incorporated [6]. Furthermore, the cost parity of RERs (such as solar photovoltaics and batteries) with the conventional generation accelerates the concept of peer-to-peer energy trading i.e., prosumers. Thus, with the utilization of MG architecture in addition to smart DERs integration, the smooth acceleration of "Energy Pro-Sumption" – *energy import and export at the user end* while balancing the supply-demand mismatch locally is possible.

The range of benefits associated with DERs, such as ancillary services, reduced system losses, improved power quality, reactive power and voltage support, deferral of capacity investment, ecofriendly nature, combined heat, and power, and stand-by generation are some of the critical driving factors in this transition to decentralization of power system. However, the inclusion of various DERs results in critical management and control issues within the MG paradigm because of their stochastic behavior. Therefore, one of the important requirements for MG's proper operation is reliability and stability.

The MG is not a new concept; it has a long history starting with Thomas Edison's first decentralized Direct Current MG in Manhattan in 1882, which was overshadowed by a centralized power network (the 1920s-1970s) due to its ability to draw a huge amount of power from distant energy resources (hydropower) and to connect multi-generation units to feed diverse load. In the 1990s, DERs benefits and carbon policies and their associated incentives brought this decentralized paradigm again into the limelight, and to date, research is active on all topics incorporated in the MG paradigm. Figure 2 demonstrates the brief history and evolution of MG [2], [4].

MGs are usually comprised of various types of RERs and DERs such as Solar Photovoltaics (PVs), windmills, hydropower plants, Diesel generation, and Energy Storage Systems (EES), and the advancement in power electronics resulted in the inclusion of a large number of these resources with MG or main electric grid. Similarly, a few MG functional classifications, topologies, and definitions are usually found in the literature [7], [8], [9], [10].

Based on the recent literature survey, substantial research conducted in MG addressing the main characteristics has been published, and selected research articles will be discussed in subsections in this paper. Additionally, many state-of-the-art surveys and reviews on MG features exist within the literature. Selected review articles are summarized in Table 1. In Table 1, "$\surd$" justify the presence of features, while "X" represents that the feature is absent in the referred study.

In light of the above-stated issues, the main contributions of this survey paper are:

Objective 1: Currently, MG is the most appropriate solution for replacing the conventional electric grid due to its reliability, efficiency, and resiliency. In order to explore the concept of advancement in MG, this survey paper thoroughly investigates the architectural model of MGs, i.e., AC MG, DC MG, hybrid MG, and networked MG (with the introduction of the new concept of dynamic electric boundaries).

Objective 2: This paper presents the communication technologies, such as wired and wireless in MG and qualitatively analyzes these in detail. Furthermore, a generalized overview of the protection mechanisms is illustrated in this paper.

Objective 3: This paper elaborates and illustrates in detail the utilization of RER-based DG, smart load, and storage techniques along with their benefits within MG. This paper also studies in detail the load classification incorporating fixed/flexible controllable load concepts and the recent trends in research in the aforementioned MG domains.

Objective 4: The overview and inclination of the recent research literature, issues, and challenges in resources, storage, and load technologies in MG are comprehensively presented in tabular form.

Objective 5: This paper surveys advanced optimization, energy management, and control methodologies deployed in MG and their interplay within MG stability and reliability scenarios.

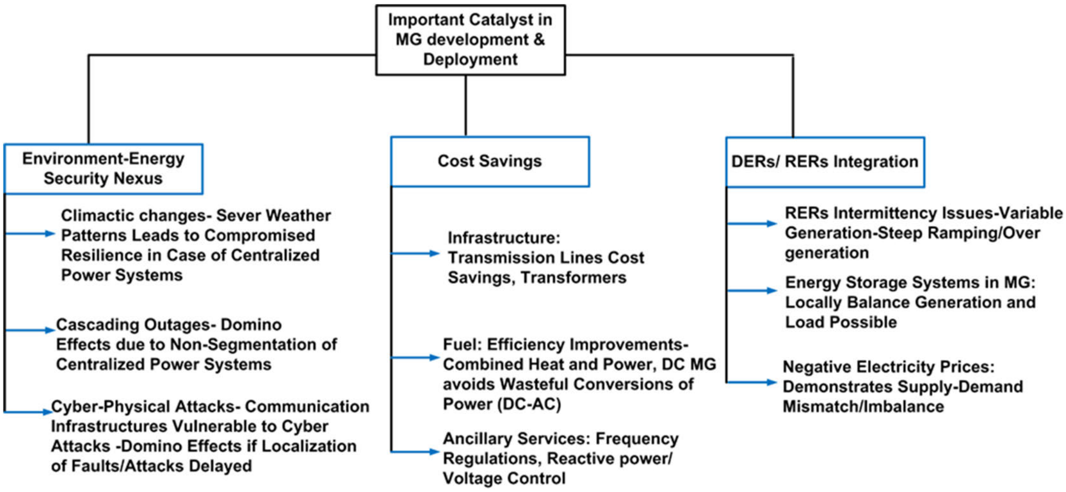

FIGURE 1. Key driving factors for microgrid deployment and development [2].

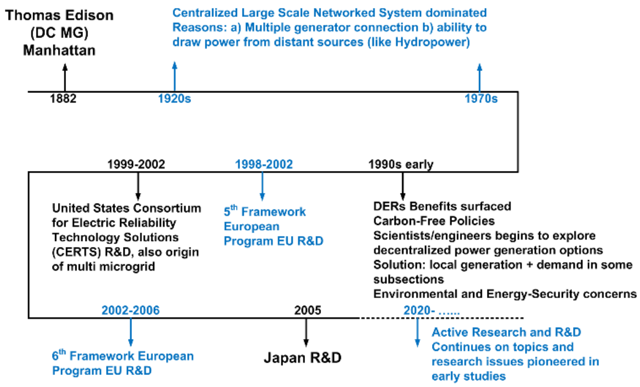

FIGURE 2. Micro-Grid (MG) evolution and history [2], [4].

Objective 6: This survey provides the qualitative analysis of some transdisciplinary technologies such as RER-based generation units, controllable loads, communication, etc. for MG.

Objective 7: Cross-sectoral impacts and challenges for MG are also elaborated on in detail. Such as impact on the economy, environment, power quality, and some associated governance issues.

Objective 8: Moreover, this study also incorporates future key development areas that include, communication, cyber security, networked MG architecture incorporating dynamic electric boundaries, advanced multi-objective and distributed optimization and control techniques, smart load participation, mobile RER-based DG units, and improved lithium-ion battery-based storage systems.

The rest of the paper is structured as **section II** presents the generalized overview of MG and key enabling technologies. MG architecture and various frameworks are illustrated in **section III**. **Section IV** demonstrates control and energy management in MG. In **section V** cross-sectoral analysis and some future research, directions are investigated. **Section VI** illustrates the future research direction and **section VII** concludes the paper with a summary.

II. GENERALIZED OVERVIEW OF MICRO-GRID AND KEY ENABLING TECHNOLOGIES

MG technology is one of the most viable and promising technologies to solve global environmental and economic problems while meeting energy demands. Consequently, a lot of the research and development in the design, energy management, operation, protection, and control of MG is dedicated in recent years to providing reliable, green, sustainable, and quality power to consumers. However, because of their stochastic nature, RERs' energy generation (intermittency) is difficult to forecast. Therefore, frequency and voltage stability, optimal power sharing and exchange between the host grid and MG, operational control, transition between grid-connected and Islanding modes, and the integration of DERs and smart load/storage system remain challenging issues.

The future of the main power grid is expected to incorporate both AC and DC technologies. Over a century, AC has remained the dominant technology; however, the rise and increasing use of renewable energy has led to the increasing use of DC devices and thus resulted in DC MG infrastructure. Renewable energy generation resources are well suited for integration with DC grid structure, and AC technology is more efficient for transmitting over long distances. Thus, the power grid will likely use this technology. Therefore, AC-DC hybrid grid infrastructure may be used to bridge the gap between AC and DC systems. The aforementioned hybrid structure can convert AC power to DC and DC power to AC. Thus, the future electric grid will likely combine hybrid AC-DC, AC, and DC structures, depending on the needs of various regions and applications.

A. KEY COMPONENTS OF MICRO-GRID

The key MG components include Energy Generation Resources (such as DERs), Loads, Communication Infrastructure, Automation and Control, Energy Storage Systems (ESS), and Protection Devices (Smart Switches) [46]. Utilization of various types of generation resources, energy storage

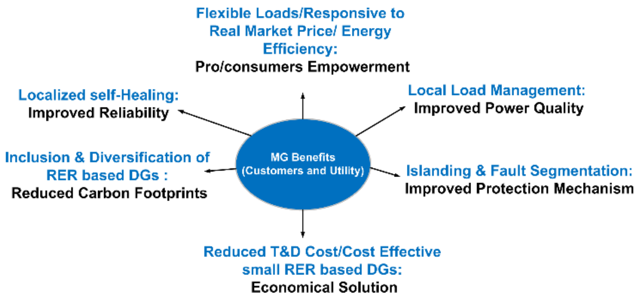

FIGURE 3. Micro-grid benefits [2].

mechanisms, load systems, and network topologies, in turn, defined different MG structures. Moreover, the MG can also be categorized based on two modes of operations, which include islanded and grid-connected [1]. DERs inside MG can be categorized as dispatchable and non-dispatchable and comprised of Distributed Generation units (DGs) and ESS.

RER based DERs fall under the category of non-dispatchable DGs and cannot be controlled by the main controller of MG. The uncontrolled input source mechanism of RER based DGs, in turn, leads to volatility and intermittency in output power-*generation uncertainty and various time scale fluctuations*. The aforementioned characteristics of RER based DG units consequently lead to forecast error; therefore, in order to guarantee adequate MG generation, these DG units are reinforced with ESS. In addition to their main application, i.e., coordination with DG units, ESS also provides ancillary services, including energy arbitrage, trading, and prosumer empowerment. The most critical role ESS plays during the islanding mode. On the other hand, dispatchable DG units are controllable, subject to various technical constraints such as unit type, capacity, ramp limits, On/Off time, emission, and fuel limits [46]. Significant advantages offered by MG include reliability, self-healing, improved power quality, reduced carbon footprints, cost-effectiveness, and increased energy efficiency. Figure 3 demonstrates in detail the significant benefits offered by MG architecture for the customer and utility grid.

Similarly, MG loads are generally sub-categorized into two main types, i.e., Controllable (flexible, responsive) and uncontrollable (Fixed, non-responsive). Non-responsive/ fixed loads cannot be curtailed, and under normal operating conditions, their requirements must be fulfilled. Flexible loads are, however, shiftable/deferable loads owing to their responsive nature to control signals such as demand response or economic incentives or islanding operation, etc. [1], [46]. The proper and smooth functioning of MG demands smart protective devices and smart switches for reasons such as connecting and disconnecting the line flows between DERs and loads, fault propagation prevention by disconnecting or localizing the fault segments, and performing islanding at the point of common coupling (PCC). The main MG controller performs the scheduling based on security and economic consideration. Moreover, this controller also determines interaction and optimal allocation of local and distributed resources. Additionally, this controller is also responsible to decide the connection and disconnection of MG with the main utility grid. However, to ensure the effective and reliable interaction among all components of MG, communication and automation infrastructures are foremost to implement [46].

Therefore, this part of the documented study presented the five main sub-sections in order to comprehensively analyze the key enabling and transdisciplinary technologies for MG proper operation. Figure 4 illustrates the generalized overview of MG components. The most salient and novel feature of MG is its islanding ability, especially during utility grid disturbance intervals, such as during voltage fluctuations, enabled by the utilization of switches at PCC. The aforementioned ability results in an uninterrupted and reliable supply to load, which is fulfilled by locally managed DERs. After the fault clearance, the resynchronization of the MG can be performed at PCC [47].

B. ENERGY RESOURCES IN MICRO-GRID

The most significant part of electrical networks is generation units (generators) or energy resources. As a consequence of the great impacts associated with these resources on MG, such as emission ratio, operational and fuel cost, power output, and structure, their investigation is the foremost requirement for MG management. Various generation resources can be used in MG, however, owing to the diverse nature of generators and energy resources, these sources can be used in different combinations in order to balance the supply-demand mismatch. The small to medium-scale DERs in MG could be placed near customers or at utility premises to provide energy support locally. Furthermore, this DER technology could potentially provide power to rural and remote areas where Transmission and Distribution (T&D) infrastructure is costly to build. Additionally, less deployment time and low construction cost compared to large conventional generation and T&D units are some of the most attractive features of this DERs technology deployment. A comprehensive and detailed overview of DERs integration and current practices in MG, along with issues related to integration, can be found in [48], [49], [50], [51], and [52].

A wide variety of technology falls under the DER category, however, most referred DERs in MG found in the literature are subcategorized as RER based DG units and ESS [50]. Clean and sustainable nature, green governance approach, and the enforcement of environmental agendas are the main drivers behind the increasing emphasis on the utilization of RER based DG units in comparison to conventional fossil fuel-based DERs. However, RER based DERs introduced vast volatilities and variability in power generation due to their dependence on meteorological factors, which is the most challenging part associated with these resources to overcome for their increased integration and incorporation [51]. Figure 5 illustrates the comprehensive overview of DG units.

The most frequently studied topic of DERs in MG is RER based DG units. An MG utilizing the RER based DG

TABLE 1. Summary of the state-of-the-art surveys.

Ref	*MG1*	*MG2*	*MG3*	*MG4*	*LM*	*GM*	*CM*	*OT*	*CEM*	*CA*	*PM*
[11]	√	x	x	x	x	x	x	x	√	x	x
[12]	√	√	x	x	x	x	x	x	√	x	x
[13]	√	x	x	x	x	x	x	x	√	x	x
[14]	√	x	x	x	x	x	x	x	√	x	x
[15]	√	x	x	x	x	x	x	x	√	x	x
[16]	√	x	x	x	x	x	x	x	√	x	x
[17]	√	x	x	x	x	x	x	x	√	x	x
[18]	√	x	x	x	x	x	x	x	√	x	x
[19]	√	x	x	x	x	x	x	x	√	x	x
[20]	x	x	√	x	x	x	x	x	√	x	x
[21]	x	x	√	x	x	x	x	x	√	x	x
[22]	√	x	x	x	x	x	x	x	x	x	x
[23]	√	x	x	x	x	x	x	x	√	x	x
[24]	x	√	x	x	x	x	x	x	x	x	x
[25]	x	√	x	x	x	x	x	x	√	x	x
[26]	x	√	x	x	x	x	x	x	√	x	x
[27]	x	√	x	x	x	x	x	x	√	x	x
[28]	x	√	x	x	x	x	x	x	x	x	x
[29]	x	x	√	x	x	x	x	x	x	x	x
[30]	√	√	√	x	x	x	x	x	√	x	x
[31]	√	x	x	x	x	x	x	x	x	x	x
[32]	√	x	x	x	x	x	x	x	x	x	x
[33]	√	√	√	x	x	x	x	x	x	x	x
[34]	√	x	x	x	x	x	x	x	√	x	x
[35]	x	√	x	x	x	x	√	√	√	x	x
[36]	x	x	x	x	x	x	x	√	x	x	x
[37]	x	x	x	x	x	x	x	√	√	x	x
[38]	x	x	x	x	x	x	x	x	x	x	x
[39]	x	x	x	x	x	x	x	x	√	x	x
[40]	x	x	x	x	x	x	x	x	x	x	x
[41]	x	x	x	x	x	x	x	x	x	x	x
[42]	x	x	x	x	x	x	x	x	√	x	x
[43]	√	x	x	x	x	x	x	x	x	x	√
[44]	√	√	√	x	x	x	x	x	√	x	x
[45]	x	x	x	x	x	x	√	x	x	x	x
OS	√	√	√	√	√	√	√	√	√	√	√

Abbreviations used in Table I:
MG1= AC MG, MG2= DC MG, MG3= Hybrid MG, MG4= Networked MG, LM= Load Classification in MG, GM= Generation in MG, CM= Communication Techniques in MG, OT= Optimization Techniques in MG, CEM= Control and Energy Management in MG, CA= Cross-Sectoral Analysis of MG, PM= Protection Techniques in MG, OS= Our Survey Paper

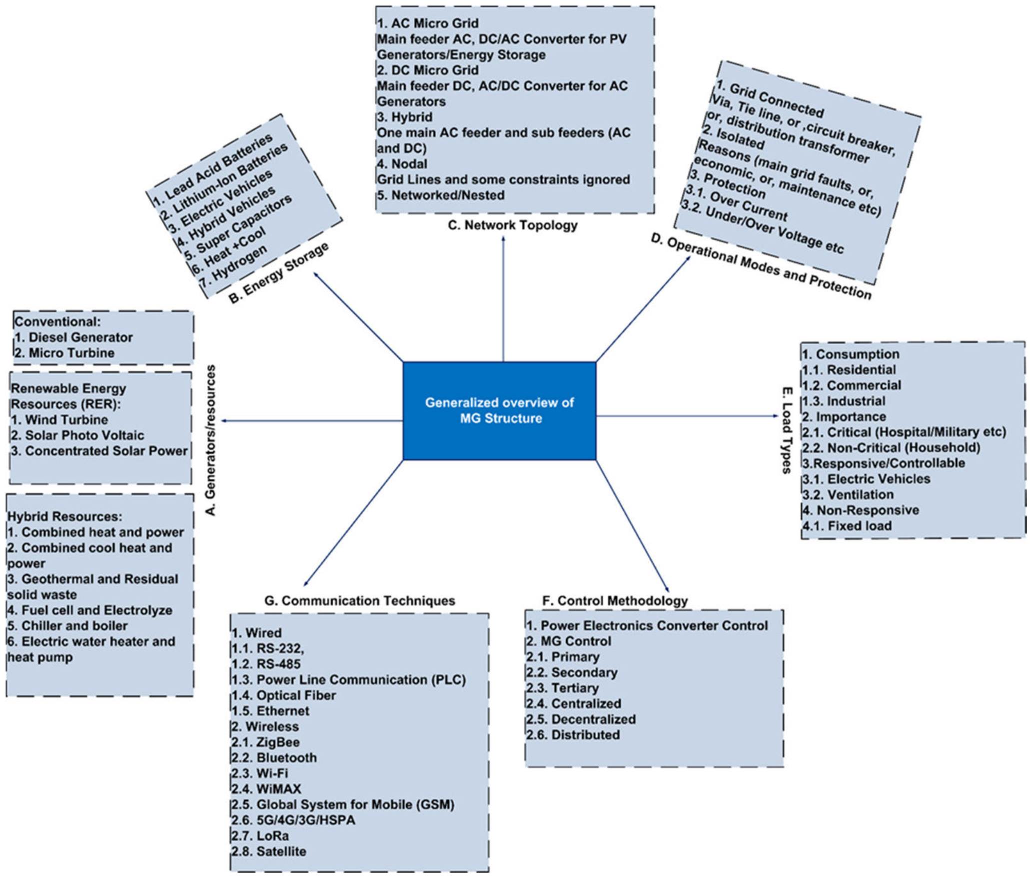

FIGURE 4. Generalized overview of micro grid structure.

units in combination with a conventional controllable gas engine for compensating the fluctuations in supply-demand is presented in [53]. The authors in [54] proposed a novel concept of urban areas where the building integrated Solar Photovoltaics (PVs) are used with the ability to run in isolation even during the grid-connected mode of operation of MG. Monte Carlo simulation framework for investigating the sensitivity of autonomous MG assembly to large integration of wind generation units is done in [55]. The authors in [55] concluded that large storage units and aggregated wind generation are needed due to variability in output power generated in such MG architectures. In [56], a rotor speed controller for the wind farm by adjusting the active power for frequency regulation in a capacity limited MG is introduced along with the incorporation of a Static Synchronous Compensator (STATCOM) for stabilization purposes during short circuit intervals.

The combined utilization of micro-hydro and microturbine is discussed in [57] for relatively weak natural energy regions. This paper concludes that MG architecture can be deployed to such regions while following some compensation mechanism between the deployed micro sources. The feasibility study related to micro-hydro plants is examined in [58], concluding that MG powered by such resources can potentially serve as a building block for system expansion and provide power to

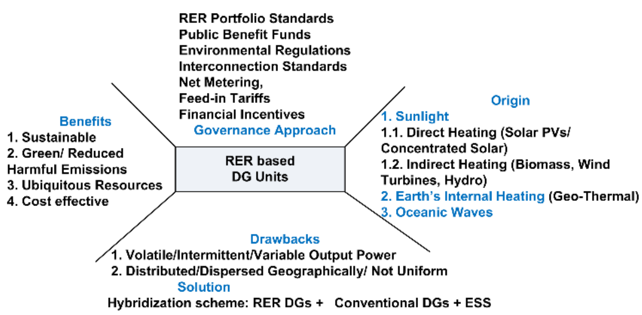

FIGURE 5. RER based DG units overview [1], [2].

rural communities. Most of the studies found in the literature related to solar power-based DERs revolve around the Maximum Power Point Tracking (MPPT) theme, which is a unique point on the characteristic Voltage- Current curve of solar cells for maximum power generation. In [59], fuzzy logic based on the hill-climbing fuzzifying method of MPPT is proposed for solar DERs. Authors in [60] proposed a modified perturb and observation technique for solar MPPT, which demonstrates the efficient steady-state performance after presenting the review and associated drawbacks of previously published studies. An intelligent neural network-based estimation technique for optimal tilt angle with an accuracy of 30o for tracking PV is investigated in [61].

In [62] investigation of the diverse mix of RER based DG units and their optimal allocation is conducted for counterbalancing the supply-demand mismatch in small MG. However, the uncertainty and highly volatile nature of RER based DGs make the islanding mode of operation an impractical approach. Therefore, to tackle this issue, a study in [63] proposed the concept of ''Provisional MG'' without the islanding ability to facilitate the expansion and integration of non-dispatchable DG units within the existing utility grid. Recently, the literature showed that conventional generation units-based DG, such as Diesel Generators (DIGs) and Micro Turbines (MTs), play a critical role in modern electrical networks due to drawbacks associated with RER based DGs. Alternatively, the low cost/investment requirements and advanced development of solar PVs and wind technology make them the most extensive studies topic in the literature.

Consequently, limited studies revolving around other types of DG units such as thermal power concentrated solar power, roof-mounted solar PVs, desalination plants in combination with Internal Combustion Engine (ICE), Tri-hybridization of Heat, Power, and Cool (TCHP), Unified Power Quality Conditioner (UPQC), solid waste, geothermal, fuel cells, microturbines, etc. are found in comparison to purely RER based DG units in MG context. Table 2 presents the energy resources deployed in the MG context found in the literature. The tabular comparison clearly illustrated that RER based DG units are the most popular for MG architectures, and their tendency has increased significantly during the past two decades. In Table 2, ''Y'' justifies the presence of features, while ''N'' represents that the feature is absent in the referred study.

C. ENERGY STORAGE SYSTEM (ESS) IN MICRO-GRID

The undeniable aspect of MG is the utilization of ESS due to DERs inclusions, their associated negative impacts, and increased load demand and growth. Thus, the islanding events and variability in output power generated by RER based DG units necessities the presence of ESS units to counterbalance the MG fluctuations. The benefits and cross-sectoral impacts of ESS within the MG context are described in figure 6. A real-time management algorithm for ESS was proposed in [106] to mitigate the effects of pulsed loads in MG. In [107], authors explain that only inverter-based MG requires ESS due to their slow responsive nature during critical management scenarios. The empirical study of vanadium redox batteries ESS based on load and weather operating requirements is done in [108]. In [109] control strategy is proposed for ESS to perform load leveling and voltage regulation, and power balancing at the same time. The ESS management comprised of high-density battery and ultra-capacitor is proposed in [110]. However, based on a recent literature survey conducted for this documented study, most of the ESS now revolves around lead-acid and lithium-ion batteries and Electrical Vehicles (EV)/Hybrid Vehicles (HV). Battery technology of EVs/HVs is used for managing

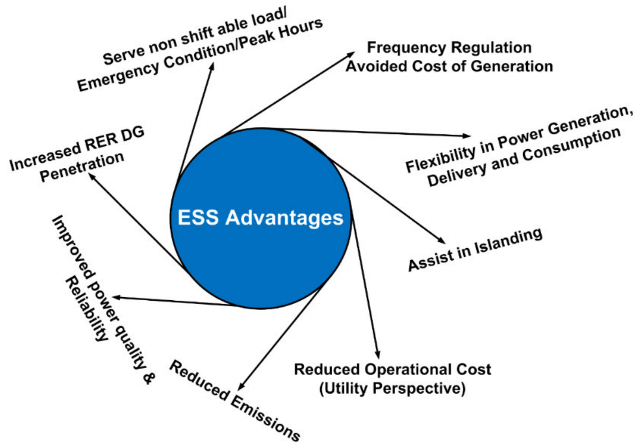

FIGURE 6. Advantages of ESS for micro-grid.

the RER based DGs [92], [94], [100], [103], [111], [112], optimal parking lot [94], [113], demand response, and smart load management [71], [100], [103], [112], [113], [114], [115], vehicle to home [116], as a frequency and harmonic compensator [78], [79], [117], [118]. Other ancillary goals achieved by ESS can be found in [98], [119], and [120].

However, zinc-based and lithium-iron phosphate batteries may offer several advantages over lithium-ion batteries in the context of MG. Zinc batteries provide higher energy density, a lower cost, and enhanced safety than lithium-ion batteries due to the absence of flammable electrolytes in these batteries. Furthermore, zinc batteries provide efficient and reliable energy storage due to high round-trip efficiency. Lithium iron phosphate batteries also offer various advantages over traditional lithium-ion batteries, such as enhanced stability under high temperatures, improved safety, and longer cycle life. Additionally, these batteries have a lower risk of thermal runaway, thus making them a safer alternative for energy storage.

Lithium-ion batteries are widely adopted as a consequence of their long cycle life and high energy density. However, zinc and lithium iron phosphate batteries may be attractive alternatives to counter the drawbacks associated with lithium-ion batteries, which include limited safety, flammable electrolytes, and high cost [252], [253], [254].

Supercapacitors are also increasingly deployed and greatly assist in studying the negative impacts of batteries, their optimal location, sizing, and charging/discharging cycles [82], [102], [121], [122], [123], [124], [125], [126]. Owing to the huge penetration of different forms of load in MG, various types of generators and storage systems are required accordingly, such as thermal and electrical or their combination. MG management strategies utilizing the heat and cool storage system are presented in [87], [88], [127], [128], [129], [130], [131], and [132]; in all these references, surplus thermal power produced by CHP and Boilers is stored for later use. In [103] and [122], hybrid ESS consisting of Lithium-Ion, Pumped Hydro Storage (PHs), and Super Conducting

TABLE 2. Summary of energy resources in micro-grid.

REF	PV	WT	DIG	FU	CP	IE	CHP	TCH	UPQC	G	CHS	MTS	STH	HPS	EH
[64]	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N
[65]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[66]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[67]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[68]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[69]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[70]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[71]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[72]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[73]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[74]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[75]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[76]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[77]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[78]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[79]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[80]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[81]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[82]	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
[83]	Y	Y	Y	N	N	N	N	N	N	N	N	Y	N	N	N
[84]	Y	Y	Y	N	N	N	N	N	N	N	N	Y	N	N	N
[85]	Y	Y	N	N	N	N	N	N	N	N	N	Y	N	N	N
[86]	Y	Y	N	N	N	N	N	N	N	N	N	Y	N	N	N
[87]	Y	Y	N	N	N	N	N	N	N	N	Y	N	N	N	N
[88]	Y	Y	Y	Y	N	N	Y	N	N	N	Y	N	Y	N	N
[89]	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N
[90]	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N
[91]	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N
[92]	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N
[93]	Y	Y	Y	N	N	N	N	N	N	N	N	Y	N	N	N
[94]	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
[95]	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
[96]	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
[97]	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
[98]	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
[99]	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
[100]	Y	Y	N	N	Y	N	Y	N	N	N	N	N	N	N	N
[101]	Y	Y	N	N	N	Y	N	Y	N	N	N	N	Y	N	N
[102]	Y	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N
[103]	Y	Y	N	N	N	N	N	N	N	Y	N	N	N	N	N
[104]	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y
[105]	Y	Y	N	N	N	N	N	N	N	N	N	Y	N	Y	N

Abbreviations used in Table II:

PV= Photovoltaic, WT= Wind Turbine, Fu= Fuel Cell, DIG= Diesel Generators, CP= Concentrated Solar Power, IE= Internal Combustion Engine, CHP= Combined Heat and Power, TCH= Tri Hybridized Heat, Cool and Power, G= Geothermal, MTS= Micro Turbine, UPQC= Unified Power Conditioner, EH= Electric Water Heater, STH= Solar Thermal, HPS= Heat Pumps.

TABLE 3. Summary of the recently published articles of ESS installed in MG.

REF	EVS	LI	LA	PHS	SME	SUC	FW	HS	HHC
[64]	Y	N	N	N	N	N	N	N	N
[65]	Y	N	N	N	N	N	N	N	N
[67]	Y	N	N	N	N	N	N	N	N
[69]	Y	N	N	N	N	N	N	N	N
[70]	Y	N	N	N	N	N	N	N	N
[130]	N	Y	Y	Y	N	N	N	N	Y
[129]	N	Y	Y	N	N	N	N	N	Y
[87]	N	Y	Y	Y	N	N	N	N	Y
[131]	N	Y	Y	Y	N	N	N	N	Y
[132]	N	Y	Y	N	N	N	N	N	N
[90]	N	Y	Y	N	N	N	N	Y	N
[91]	N	Y	Y	N	N	N	N	Y	N
[119]	N	Y	Y	N	N	N	Y	N	N
[122]	Y	Y	Y	N	Y	Y	N	N	N
[103]	Y	Y	Y	Y	N	N	N	N	N

Abbreviations used in Table III:
EVs= Electrical Vehicles, LI= Lithium-Ion Battery, LA= Lead-Acid Battery, PHS= Pumped Hydro Storage, SME= Super Conducting Magnetic Storage, SUC= Super Capacitor, FW= Fly Wheel, HS= Hydrogen Storage, HHC= Hybrid Heat and Cool Based Storage

Magnetic Storage (SME) is proposed as a consequence of their increased storage capability, voltage regulation, and less time delay. To store the surplus electrical energy, hydrogen storage is used [68], [89], [90], [91], [92]. These Studies illustrated that the low cost and variability of lithium-ion and lead acid batteries are the main reasons behind their increased deployment in MG's ESS management. However, the technologies based on SMEs and PHs are rarely reviewed in the literature. Table 3 presents the installed ESS in MG during recent years' studies.

D. LOAD CLASSIFICATION IN MICRO-GRID

In modern power networks maintaining the balance between system demand and scheduled generation is one of the most critical functional requirements for the reliable operation of these networks. With the advent of advanced metering infrastructure and the implementation of demand side management programs, now the load in the MG setting can also participate in energy management. This new concept is also referred to as load response or demand response. The techno-economic benefits of the aforementioned concept include reserves for long-term generation planning, enhanced T&D investment, and improved operational efficiency [133].

Therefore, the consumer's load has transformed into controllable and smart resources or sinks as required while participating in demand response management programs. Other ancillary services provided by this concept include grid balancing either by shifting the loads in real-time (during peak power generation time) or by shifting them to off-peak time (load shaving mechanism) [134]. Furthermore, this load management approach greatly assists in achieving multiple other goals, such as optimal load distribution, reduced cost and pollution emission, and improved reliability. The loads in MG can be categorized into four main types: (i) importance, (ii) consumption, (iii) responsive, and (iv) nonresponsive nature. Critical (hospital and military etc.) and non-critical (household etc.) fall under the first category of MG load classification [64], [70], [71], [73], [76], [88], [92], [102], [104], [116], [118], [121], [125], [131]. In the consumption category, residential, commercial, and industrial subcategories are defined based on the amount and dimension of load demands [66], [70], [71], [75], [77], [83], [98], [101], [102], [113], [115], [122], [125], [128]. The load categorization based on the responsive nature includes flexible and curtailable loads, which include ventilation systems and electric vehicles etc. [66], [83]. The fourth category of load classification is uncontrollable fixed loads, i.e., without any communication channel between consumers and utility [64], [73], [76], [92], [99], [104], [116], [118]. Table 4 summarizes the recent studies found in the literature for the load categorization of MG.

E. ISLANDING DETECTION TECHNIQUES

Islanding phenomena occur during power outages when the main grid is disconnected, and the MG continues to supply the power to local loads. However, it may result in unexpected voltage and frequency fluctuations and can be dangerous for workers restoring the power connection. Consequently, it is essential to quickly detect islanding and disconnect the MG from the main power grid in order to avoid safety hazards. Some commonly used islanding detection techniques include [228], [229]:

- **Passive Techniques:** The passive techniques rely on the changes in frequency and voltage of MG during the islanding mode, such as the Rate of Change of Frequency technique measures the frequency deviation of MG from the main power grid (nominal) frequency, which is also referred to as frequency shift technique. Similarly, the vector shift technique is used to measure the phase deviation of voltages between MG and the main grid, and if this difference exceeds a certain threshold, then it indicates the disconnection of the main power grid.
- **Impedance-Based Techniques:** The impedance based techniques measure the impedance of the MG and compare it with a predefined value. If the impedance exceeds the aforementioned value, it indicates the islanding of MG.
- **Active Techniques:** Active techniques involve the injection of small signals into MG to detect the islanding, for instance, in the case of the active frequency shift technique, a small frequency deviation is injected into MG and monitors whether the main power grid responds to it or not.
- **Hybrid Techniques:** These techniques combine both passive and active techniques to improve islanding detection accuracy.

F. MG PLANNING TECHNIQUES

MG planning involves designing and optimizing the operation, configuration, and size of components within MG ensuring to meet the energy demands of local loads. There are several MG planning techniques, and Table 5 also demonstrates some of the optimization techniques used in the MG context. However, some commonly used MG planning techniques are [230]:

Mixed-Integer Linear Programming: This technique is the extension of linear programming and incorporates the binary and integer decision variables.

Nonlinear Programming: This technique involves the optimization of nonlinear objective functions subject to nonlinear constraints and is used for nonlinear characteristics of the system components [231].

Rule-Based Approaches: These approaches utilize a set of rules to determine the size of MG components, such as the size of the storage system may be determined by the expected duration of power outages, etc. Some examples of rule-based approaches used for MG planning include Rule-Based Heuristics and rule-Based Expert Systems etc. [232].

Simulation-Based Approaches: These approaches use simulation tools to model the behavior of the MG components and evaluate different design and operation scenarios [230], [231].

G. COMMUNICATION TECHNOLOGIES IN MICRO-GRID

Based on the recent literature survey, automation and smartness of MG are achieved because of the deployed communication structures and are one of the key factors behind intelligent and optimal management, control, and protection of MG [135], [136], [137]. Therefore, depending on scenarios such as geographical location, protection, management, number of DERs, load importance, and control mechanisms, several communication protocols and configurations have been applied in MG. Moreover, the communication technology deployed in MG is categorized into two sub-groups: wired and wireless. The most prominent international standards include the International Electro-Technical Commission (IEC) and the Institute of Electrical and Electronics Engineering (IEEE) [138], [139], [140], [141]. These standards and types of communication technology used in MG are comprehensively illustrated in figure 7.

Furthermore, the research trend in MG is usually dichotomized into electrical and communication because the performance of the first is highly dependent on the second. Thus, several research studies have attempted to define the architecture, technologies, and requirements of communication infrastructure in MG. Authors in [148] classify communication into three levels that include Home Area Network (HAN), Field Area Network (FAN), and WAN, and further define appropriate technologies for each level. They concluded that wireless technology could be a more efficient solution for use in MG in comparison to wired one as a consequence of physical constraints associated with wired technology. Security, reliability, complexity, and Quality of Service (QoS) are some challenges mentioned in this study. A comprehensive survey on MG communication technologies and testbed can be found in [149], in which authors reviewed the implemented communication infrastructure in MG, however, future trends and directions are missing in this article. The study in [150] presented the challenges associated with the deployment of wireless technology in MG. Feasible network topology for MG is demonstrated in [147] and presents the challenges related to the smartness of MG,

TABLE 4. Summarized version of recent literature for load categorization in MG.

REF	RES_L	C_L	IN_L	CR_L	$NONCR_L$	R_L	$NONR_L$
[64]	Y	N	N	N	Y	N	Y
[121]	Y	N	N	N	Y	N	Y
[73]	Y	N	N	N	Y	N	Y
[99]	Y	N	N	N	Y	N	Y
[76]	Y	N	N	N	Y	N	Y
[92]	Y	N	N	N	Y	N	Y
[104]	Y	N	N	N	Y	N	Y
[118]	Y	N	N	N	Y	N	Y
[66]	Y	N	N	N	Y	Y	N
[115]	Y	N	N	N	Y	Y	N
[83]	Y	N	N	N	Y	Y	N
[87]	Y	N	N	N	Y	Y	N
[98]	N	Y	Y	N	Y	N	Y
[75]	N	N	Y	N	Y	Y	N
[131]	Y	N	N	Y	N	Y	N
[88]	Y	N	N	Y	N	Y	N
[95]	Y	N	N	N	Y	Y	N
[130]	Y	N	N	N	Y	Y	N
[132]	Y	N	N	N	Y	Y	N
[100]	Y	N	N	N	Y	Y	N
[103]	Y	N	N	N	Y	Y	N
[127]	Y	N	N	N	Y	Y	N
[69]	Y	N	N	N	Y	Y	N
[97]	Y	N	N	N	Y	Y	N
[93]	Y	N	N	N	Y	Y	N
[114]	Y	N	N	N	Y	Y	N
[128]	Y	Y	N	N	Y	N	Y
[101]	Y	Y	N	N	Y	N	Y
[70]	N	Y	N	Y	N	N	Y
[85]	Y	N	N	N	Y	Y	Y
[113]	Y	N	Y	N	Y	Y	N
[71]	Y	Y	N	Y	N	N	Y
[125]	Y	Y	N	Y	N	N	Y
[122]	Y	Y	Y	N	Y	Y	N
[102]	Y	Y	Y	Y	N	N	Y

Abbreviations used in Table IV:
ResL = Residential Load, CL = Commercial Load, InL = Industrial Load, CrL = Critical Load, NonCrL = Non Critical Load, RL= Responsive Load, NonRL = Nonresponsive Load

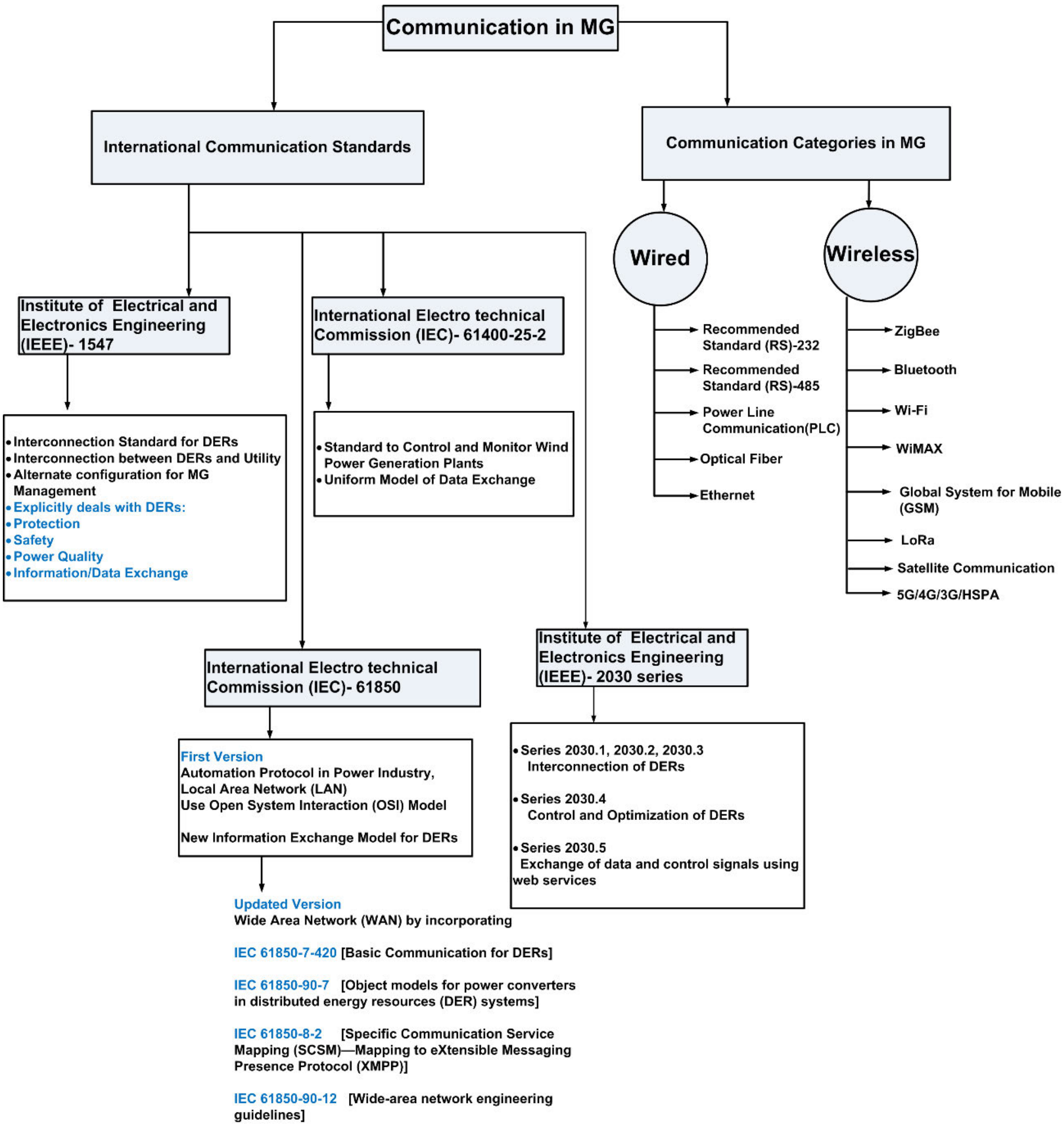

FIGURE 7. Communication types and standards deployed in MG [45].

such as bandwidth, cybersecurity, reliability, and latency. The clarified study about data flow and communication protocols for MG – Internet Protocol Suites, Modbus, DNP3, and IEC standards can be found in [151].

The efficient and appropriate communication technology in MG depends on different hierarchical levels in MG and their associated specifications and constraints (involved in information exchange). Different control levels in MG, such as Advanced Metering Infrastructure (AMI), Demand Side Management (DSM), and Energy Management System (EMS), require highly secure and reliable communication infrastructure, however, their delay and data rate characteristics vary according to their coverage characteristics. Moreover, the most important requirement for communication structure in MG is backup power. These backup power phenomena are critical during an outage interval. Furthermore, this requirement is also proportional to various levels of control in MG, such as 72 hours for DSM to one hour for EMS. In parallel to hierarchical control levels in MG, communication infrastructure can also be divided into a hierarchy (like Smart Grid) that includes three different levels: Home Area Network (HAN), Field Area Network (FAN), and Wide Area Network (WAN). Starting with HANs, the home energy management system via controlling smart loads that include Electric Vehicles and certain appliances greatly assisted in utility-based demand response programs (such as Real-time pricing and direct load control, etc.). Similarly, FAN assisted in coordination among various RER DGs, operators, and ESS

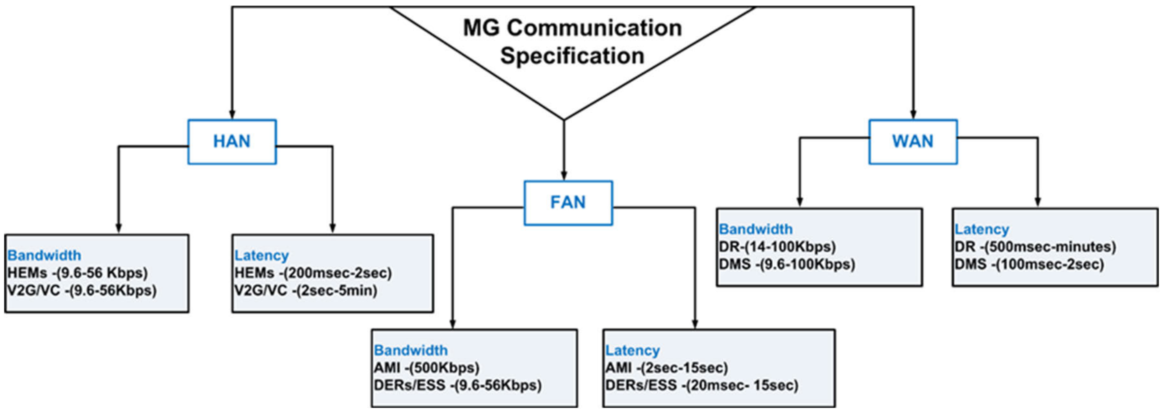

FIGURE 8. Communication specification of MG [152].

and thus required much higher bandwidth as compared to HANs. At the highest level of this communication hierarchy, WANs embrace the exchange of information during the grid-connected mode, which means the coordination between EMS and DSM. Figure 8 demonstrates the communication specification of MG [152].

1) WIRED COMMUNICATION TECHNOLOGY IN MICRO-GRID

At the HAN level, the wired technology used in MG usually consists of Power line communication (PLC) and ethernet, while at the FAN level, coaxial cable and Digital Subscriber Line (DSL) are used in addition to PLC and ethernet. Finally, at WAN, fiber optics are used. The proliferation and interaction of various sensors, actuators, controllers, and AMI made communication structure an inevitable part of MG. In the case of MG, especially when it is located in rural/remote areas, the implementation of wired communication technologies costs more in comparison to wireless. However, the associated advantages of this technology are fewer interference issues and non-dependence on battery power as compared to wireless technology. The PLC, a widely and extensively used communication technology in power systems due to lower implementation costs, is broadly categorized into three types for MG applications. These three types include Broadband PLC, narrowband PLC, and ultra-narrow band PLC. Applications and characteristics of wired technologies are presented in figure 9 [153], [154].

Some advantages and disadvantages of wired technologies are (i) coaxial cable; advantages are easy installations and lower cost, but lower bandwidth with high susceptibility to noise are disadvantages, (ii) ethernet; merits include high reliability, security, and capacity while demerits are complexity and less ideal performance in real-time (iii) DSL; economical solution but poor data quality is the main drawback, (iv) fiber optics; benefits are on-interference of noise (electromagnetism), high security, and good latency, however, low scalability and expensive nature are biggest demerits of this technology, (v) PLC; already existed infrastructure utilization make this technology a cost-effective one but sensitivity to weather and power grid noises are downsides of this technology.

2) WIRELESS COMMUNICATION TECHNOLOGY IN MICRO-GRID

Wireless technologies, including cellular networks, satellite systems, wireless LAN, Personal Areas Networks (PAN), and lower power personal WAN, are attractive candidates for deployment in MG due to their cost-effective nature and reduced complexity. The prominent and widely used technology in HAN and AMI is Zigbee, which can provide three different topologies: star, tree, and mesh. Reduced energy consumption, lower cost, and the utilization of an unlicensed 2.4GHz band are some key factors behind the wide adaptability of Zigbee. However, the biggest demerit is the huge risk of interference with this technology. Another appropriate communication technology for HAN and FAN is Wireless Fidelity (Wi-Fi) because of its increased penetration into internet infrastructure. For WAN, it is implemented under IEEE 802.11. To facilitate the peak shifting mechanism, especially in the HAN scenario (AMI), Worldwide Interoperability for Microwave Access (Wi-MAX) is reported among the most appropriate technologies, operating in the licensed 2.5 or 3.5 GHz spectrum, but they are expensive for deployment in MG and operate under IEEE standard 802.16.

The better data rate and bandwidth of cellular technologies such as Global System for Mobiles (GSM), General Packet Radio Service (GPRS), 3G, 4G/5G, etc., are the important catalysts behind the usage of this technology in the WAN scenario for exchanging information among various meters, control, and supervisory level in MG. However, the cost associated with the licensed spectrum and severe sensitivity to weather conditions is critical drawbacks. Long Term Evaluation Advanced (LTE-A), known as 4G, is the developed version of conventional analog signal communication techniques and is also advanced in terms of data ranges compared to its predecessor, 3G. Further noticeable advancement is introduced by 5G to incorporate Internet of Things (IoT) applications in MG. Moreover, 5G technology with three

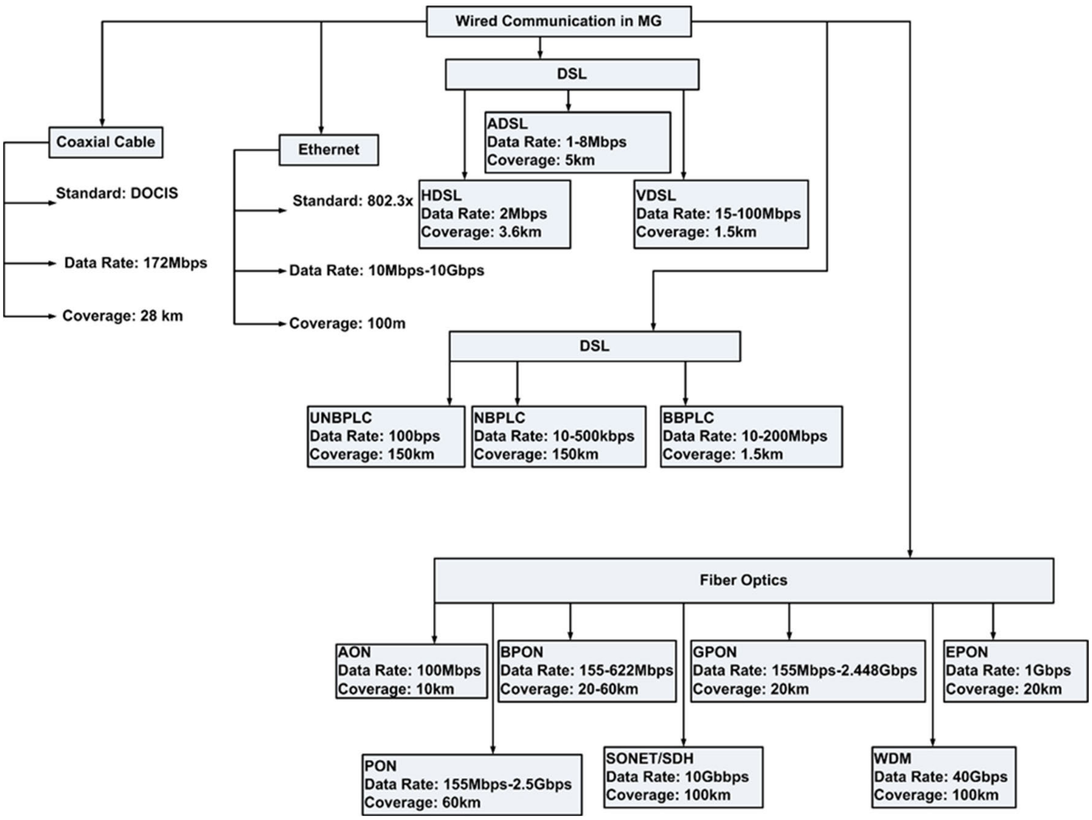

FIGURE 9. Wired technology in micro-grid [153], [154].

characteristics, such as Multi-In-Multi-Out, Millimeter-wave (mm-wave), and ultra-dense network, introduced extra benefits of higher bandwidth, incorporation of larger nodes, higher security, and lower latency rate. The services offered by the 5G, as determined by the International Telecommunication Union, include ultra-reliable and low-latency communication, enhanced mobile broadband, and massive machine-type communication. The massive machine-type communication can support up to 1 million per Kilometer square connected devices, thus facilitating the implementation of IoTs in MG (smart home) [155]. The data rate and energy consumption equilibrium in WAN settings is achieved by introducing the long-range (LoRA) and SIGFOX in cellular networks. The usage of star topology resulted in simplicity and reduced power consumption [156].

The communication requirement of remote area MG can be fulfilled by satellite technology. Additionally, this technology may be used for creating backup by providing redundant channels. Satellite technology is subcategorized into low and medium earth orbits and geostationary orbits. The main demerits of this technology are the high latency rate and cost [157]. Figure 10 demonstrates the wireless technologies in MG [45].

H. PROTECTION MECHANISM IN MICRO-GRID

The direct coupling and interconnection of various DGs in MG are infeasible thus, power converter-based interfacing is required for the proper synchronization of these units [158]. However, this interfacing scheme based on power electronic converts introduced certain protection challenges, especially in the case of inverter-dominated MG. Furthermore, the curtailment of output currents in converters may undermine the accuracy of conventional protection techniques for fault currents [159]. Therefore, in the literature, some authors proposed the idea to accommodate dynamic behaviors of fault currents by using directional and adaptive features [160], [161], [162]. In the study [15], online and offline monitoring of the state for accomplishing the automatic relay settings to respond to a fault condition is demonstrated. Intelligent optimization techniques to optimally place DG units to assist in protection coordination are presented in [163] and [164]. The authors in [165] and [166] illustrated the wide-area protection and monitoring scheme for smart MG using Phasor Measurement Units (PMUs) and showed that the global synchronization mechanism of PMUs greatly contributed to the smart management of MG.

Primarily, one of the key factors behind the inconsistent current magnitude in MG is the stochasticity and intermittency of RER based DGS. Moreover, the nature of the fault current is dependent on the type of DG as well as in the case of Micro-Hydro DG Units, the transients (high initial fault currents) are very high before reaching the steady state because of the involvement of synchronous machines in these DG Units (energized field windings) [167]. However, in the case of induction machine-based DGs, the fault currents are initially high but decay very fast and reach steady-state

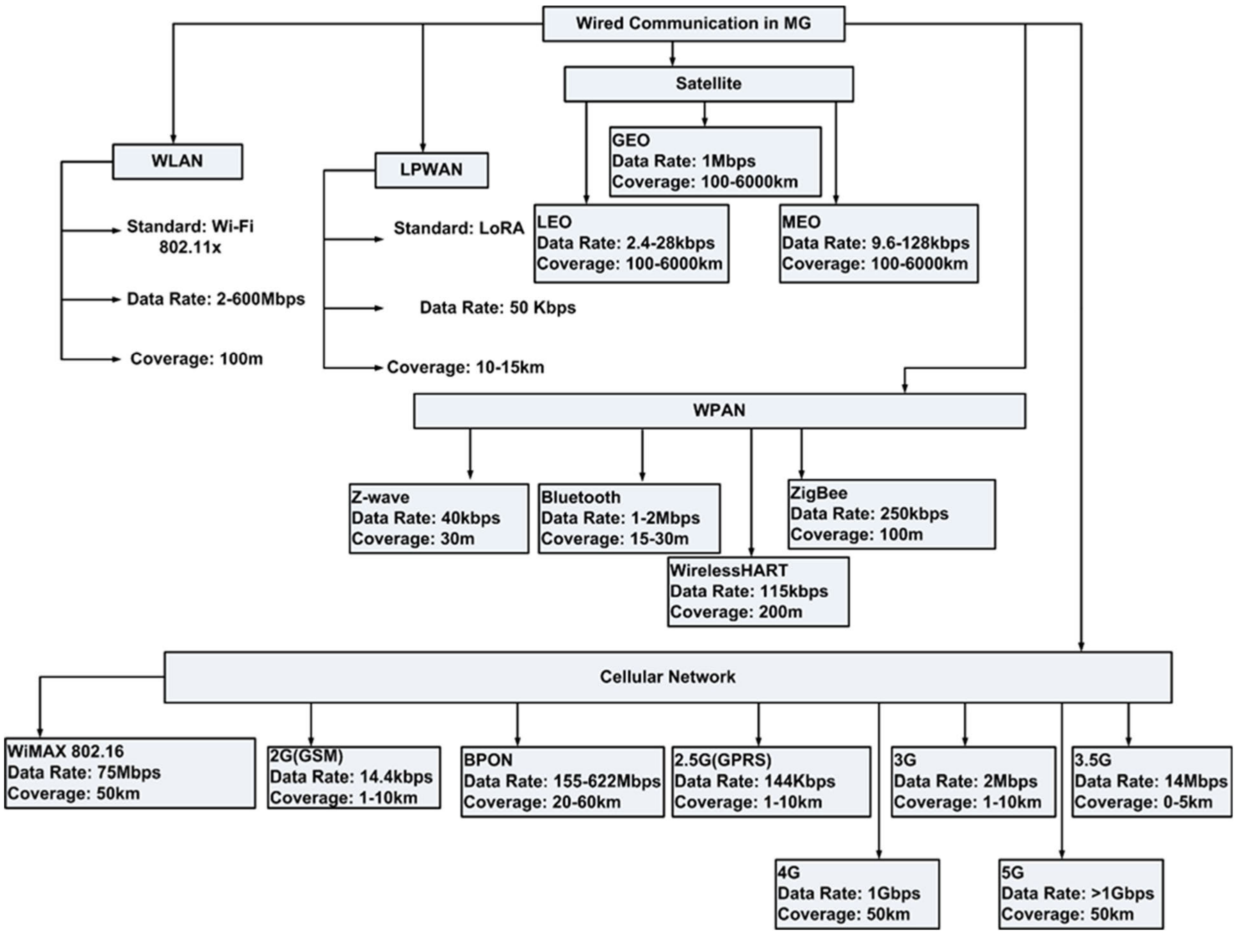

FIGURE 10. The wireless technologies in MG [45].

promptly. While in inverter-dominated MG, due to lack of inertia, the fault current is restricted to twice the rating of the converter, and the transient in this case, usually decays down within 0.5 cycles and is dependent on the time constant of the system as well. Similarly, converter voltage and control strategies greatly influenced the behavior of fault currents in MG, such as in voltage control techniques, the link-capacitor tries to maintain the constant voltage during fault interval but introduces high inrush currents [168], while in current control case, gradual rise and decay of fault currents are observed [167], [168]. Moreover, inverter fault currents are also highly influenced by the switching frequency [168]. In the case of wind power generation, various fault ride-through capabilities and grid code conformity can be found in [169], [170], and [171].

Finally, the grounding mechanism of MG directly impacts fault and protection. TN (Earthing Letter Code) grounding strategy is preferred for low voltage MG, in both grid-connected and islanding modes of operation, because of its highly responsive nature to activate the protection system in MG [172]. Similarly, transformer interfacing configurations such as Δ/Δ, Y/Δ, and Δ/Y_g are highly preferred because of their ability to inhibit the ground and zero sequences resulting in blockage of fault current flow to the grid side [173], [174]. Figure 11 illustrates the general classification of MG protection schemes.

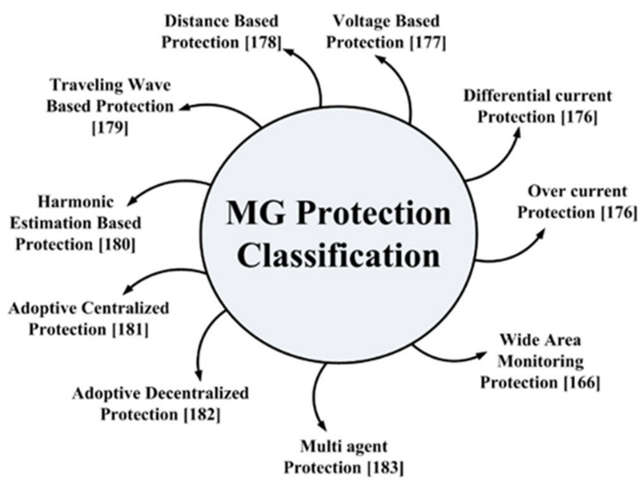

FIGURE 11. General classification of MG protection schemes.

The modernization of the power system started with the inclusion of SCADA but resulted in information lag due to their slow and unsynchronized measurement architecture, unable to support the vast data exchange of modern MG. However, incorporating PMUs facilitates real-time data exchange due to their low latency and time-synchronized mode of operation, hence contributing toward the smart MG paradigm.

The future protection scenario of MG is moving towards distributed and decentralized, i.e., closed-loop protection, in order to localize the fault area within MG timely. This idea, usually referred to as self-healing, necessitates the modern communication infrastructure, sensors, actuators, and intelligent control strategies as well. Also, data parallelism is an emerging concept for energy management and the protection of MG [43].

III. MICRO-GRID ARCHITECTURE AND VARIOUS FRAMEWORKS

MG, by regulating and distributing the flow of electricity, can be considered as a modern and smaller version of a conventional centralized power system. However, unlike the centralized electricity system, it is done locally. Moreover, MG is also considered in a single controlled and aggregated load unit in the modern power system [183]. Furthermore, MG usually has two paramount features, namely plug-and-play and peer-to-peer energy systems. In a plug-and-play scenario, RER and conventional DG units can be flexibly positioned at any location without the requirement to reconstruct the protection schemes. While in peer-to-peer cases, the absence or inclusion of a master controller or centralized storage system will have no impact on the operation of MG. These two features not only facilitate the inclusion of smaller and RER-based DG units but also greatly assist in reducing the possibility of engineering errors within MG.

A. OPERATIONAL MODES OF MICRO-GRID

MG may operate in two modes, such as Isolated and grid-connected modes, and the associated operational requirements of these modes greatly differ.

1) ISOLATED MODE

MG can detach and function autonomously in this mode of operation, especially during grid disturbance intervals (fault on the main grid) or when perturbance in power quality occurs. MG maintains high power quality and a reliable/ continuous power supply to consumers without interruptions by operating in this mode of operation. Disturbance events such as frequency drops and voltage sags may occur on the main electricity grid. Therefore, this unique feature of MG to detach from the power grid is famously known as Islanding [184], [185], [186].

2) GRID-CONNECTED MODE

This mode is the normal operating mode of MG, in which, depending on the accumulative power demand and supply, MG can export or import power to the main electricity grid. During this mode of operation, the bi-directional flow of power (import/export) is also maintained by MG, and MG continues operation in this mode until power perturbance or fault occurrence. Furthermore, in this mode, MG can also feed its entire load. Figure 12 demonstrates the two operational modes of MG.

B. MICRO-GRID CONFIGURATION

1) AC MICRO-GRID

In this configuration, all loads and generation resources are connected to a main and common AC bus. This configuration is further sub-categorized into three types based on distribution system structure that includes single-phase, three-phase without neutral, and three-phase with neutral line. The main components in this configuration that required synchronization are unbalanced, harmonics, and active and reactive power. Therefore, the control and management of AC MG are complex in comparison to DC MG. In DC MG, control is less complex because the main component to control is DC power [187].

AC loads can be directly fed from the main bus without any power conversion mechanism. However, the DC power generation of PV requires DC-AC inverters, and to feed the DC loads, rectifiers are used to convert AC to DC power. To handle the active and reactive power of wind generation units, a combination of converters is used in this configuration. Interfacing AC MG with the main electricity grid is simpler as a consequence of only the phase-matching requirement [188]. Merits of AC MG include the utilization of high-efficiency transformers, easy extinguishing mechanisms of fault arc current at zero crossing (reliable circuit breaker performance), independent control of reactive power, and voltage stability. Some demerits associated with this configuration are the conversion of AC power for DC loads (modern electronic devices etc.) greatly impact the efficiency of the system, the introduction of harmonics, and the inclusion of inverters for interfacing DC RER based DG units [188]. A generalized overview of the AC MG structure is presented in figure 13.

2) DC MICRO-GRID

In this architecture, the main bus is DC, hence DC loads can be integrated directly without any power conversion, thus having high efficiency and reduced cost. However, for AC loads, inverters are required for interconnection with the main DC bus. The increased deployment and development of RER based DG units (DC in nature) have accelerated the research in recent years in this area of MG architecture. In the case of wind generation, the output power generated by wind turbines is AC in nature, therefore, this power is integrated into DC MG by using AC-DC converters. While in the PV case, DC-DC boost converters are used with the basic goal of maximum power point tracking mechanism.

Advantages of DC MG include direct interconnection of the battery storage system (backup power), ease in the integration of RER-based DC DG units, the inclusion of simple inverter units for the grid-connected mode of operation,

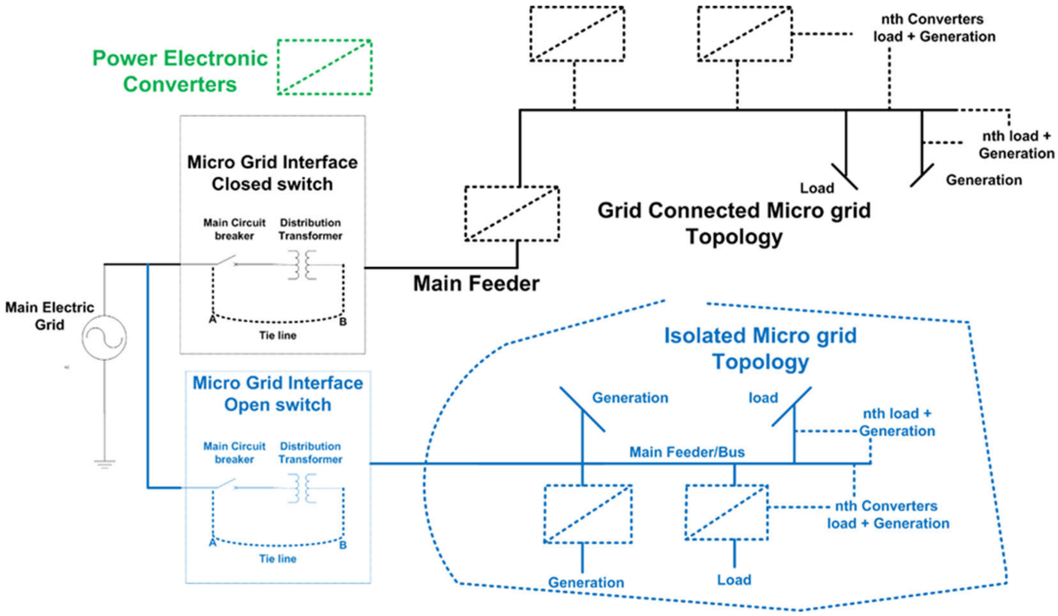

FIGURE 12. Operational modes of micro-grid.

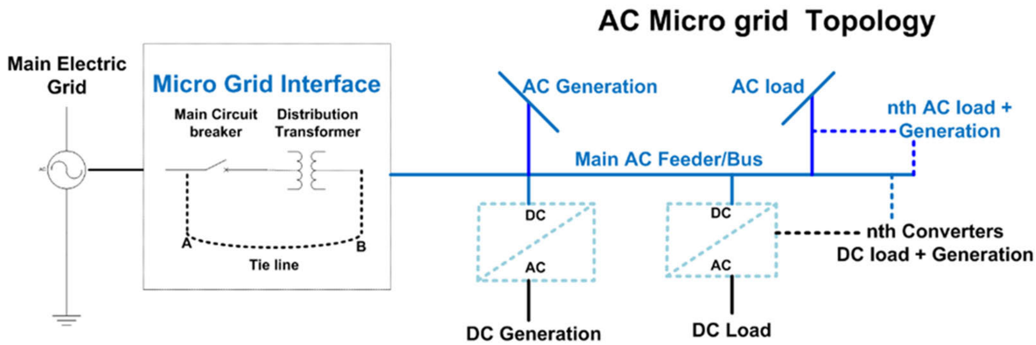

FIGURE 13. Generalized overview of the AC micro-grid structure.

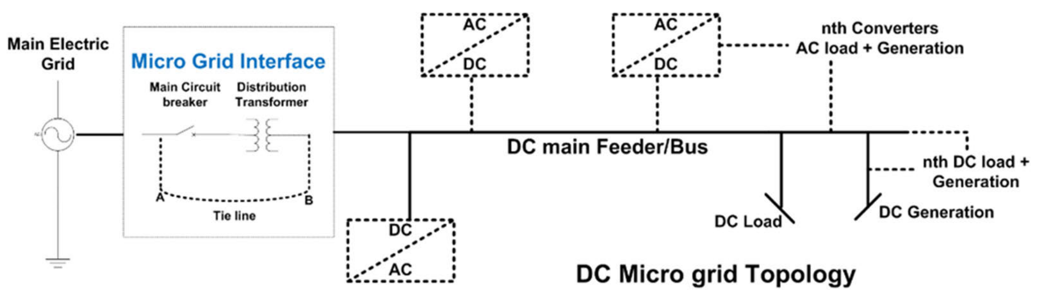

FIGURE 14. Generalized overview of the DC micro-grid structure.

reduced cost, and high efficiency (less power conversion requirement). The main drawback of this structure is that most of the load units need AC power. Other drawbacks are less systematized voltage transformation and the inclusion of a rectifier for AC generation units. Figure 14 illustrates the generalized overview of DC MG.

3) HYBRID MICRO-GRID

The hybridization of both DC and AC MG architecture resulted in the incorporation of the advantages of the aforementioned structures. In this configuration, the flow of power between networks and the utility grid is controlled by a power electronic interface and static transfer switches, respectively.

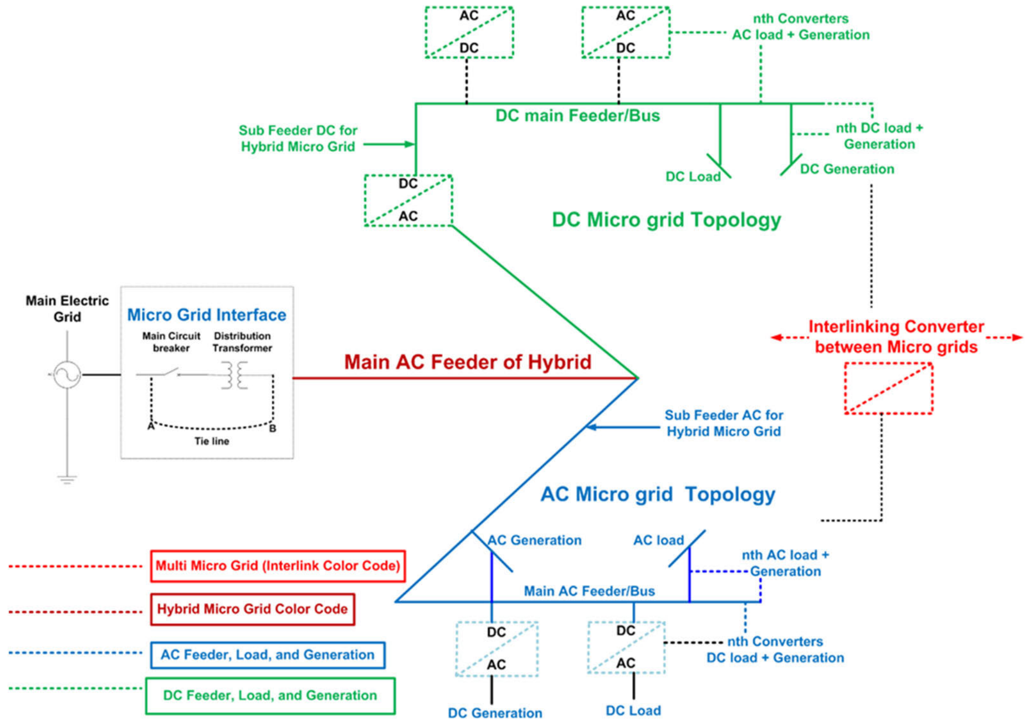

FIGURE 15. The hybrid micro-grid structure.

The balance between supply-demand/load-generation determines the power direction in this configuration. The key factors behind this architecture are to improve overall efficiency by reducing energy costs and conversion stages. Interfacing AC-DC MG utilizes bi-directional AC-DC converters, and DC-DC boost converters are used for connecting DC generator panels to the sub-bus (DC main) in DC MG. While DC-DC buck converters are required for DC loads (EVs, etc.), and energy storage technology interconnection needs a bi-directional DC-DC converter in sub-sectioned DC MG of hybrid MG configuration. The interlinking converter between AC and DC sub-sectioned MG functions according to the overload condition of these sub-sections. During the overloaded condition of AC-MG, this converter will act as an inverter, and the power flow direction is from DC to AC MG. Similarly, during the overload condition of DC MG, this converter (interlinking) acts as a rectifier, following the power flow direction from AC to DC MG.

Therefore, this interlinking converter is referred to as the main converter in most of the literature studies on MG and governs the power flow between sub-sectioned MGs inside the hybrid MG architecture. Furthermore, this main converter also stabilizes the bus voltage in DC MG [188]. Advantages of hybrid MG include reduced conversion loss, enhanced local load support, plug-and-play type management of individualized DC-AC MG sub-section, and reliable ancillary services. The biggest demerit of this configuration is the interrelationship of sub-section MG architectures. This makes this configuration highly complex and introduces numerous operational issues and greater difficulty in DG units' assimilation with two distinct sub-sectioned MG portions [188]. Figure 15 presents the hybrid MG structure.

4) NETWORKED MICRO-GRID

The clustering of MG that have functional interoperability and physical interconnection is referred to as networked MG. In this configuration, various MG units are integrated into distribution feeders incorporating fixed or dynamic electric boundaries via centralized or distributed control and intelligence. The utility companies adopting this configuration are Commonwealth Edison (ComEd), Illinois Institute of Information Technology Chicago, ConEd, and Chattanooga Electric Power Board [189]. Another novel concept, "nested" MG, within this configuration is invested by the New Paltz MG project [190] to divide the MG into "nodes: that are responsible within their respective geographic footprints. The formation and operation of this configuration can occur in various manners depending on technical and operational objectives. The two general classifications of this networked architecture include fixed and dynamic electric boundaries. In a fixed electric boundary, the overall electric boundary is defined after the merging of fixed boundaries of interconnected MGs (clustering of MGs). This overall boundary is naturally defined by switches and PCCs. Multiple MGs are interconnected within fixed boundaries in order to balance the load demand. While with the help of frequency and voltage regulation mechanisms, dynamic adjustment of electric boundaries of nested MS is also possible. These boundaries are flexible and operated by the utilization of switch gears, which may act as temporary PCCs for new boundaries. This flexible approach also leads to the concept of "Virtual" MG.

In literature, this dynamic boundary concept is also referred to as grid sectionalization and greatly assisted in the self-organizing and inclusion of RER-based DG units. The virtual MG concept is similar to the Virtual Power Plant MG concept but with the additional grid-forming ability and the incorporation of heterogeneous generation, storage, and load components. Similarly, the nested MG concept is very close to the concept of multi MG, in which several MG are interconnected through electric links in order to improve efficiency and facilitate power exchange. All these novel concepts expand and enhance the operational flexibility of grid structure by incorporating efficiently all grid assets [189].

IV. CONTROL AND ENERGY MANAGEMENT IN MICRO-GRID

MG requires proper control strategies for establishing a stable system by coordinating various micropower types. The control objectives revolve around active and reactive power, correction of imbalance (voltage/system), and load dynamic requirements. The control within MG is broadly classified into source/load, central, and distributed control. The functionality of the MG control mechanism is categorized into three subsections such as interfacing upstream (networked/multilevel), overall MG control, and local protection.

A hierarchical/multilevel control scheme is applied in MG because all time scales of the power system are of concern for stable operation. This hierarchy in MG is further divided into primary, secondary, and tertiary levels. The tertiary level, the highest in the hierarchy, is used to coordinate between MG and the host power network, while the remaining two levels are associated with the management and control of MG to maintain its power balance.

The basic control architecture followed by MG are the approaches based on centralized, decentralized, distributed/ multi-agent, and the position of the central controller determines the centralized or decentralized control structure within MG. In centralized control methodology in MG, the main/central controller communicates and processes the information transmitted from every subsystem (DERs/Load) incorporated in the system, but this control approach is not considered a robust scheme for implementation, as demonstrated in figure 16.

While in distributed approach, control efforts are distributed among cooperative autonomous agents for achieving global objectives, thus resulting in a highly scalable and robust system. The distributed control in MG is illustrated in figure 17.

The decentralized control architecture is implemented in a non-cooperative way by using the local measurements of distributed autonomous agents only and is generally based on voltage-frequency droops. However, the decentralized approach is challenging to implement at the secondary and tertiary levels due to a lack of communication/cooperation

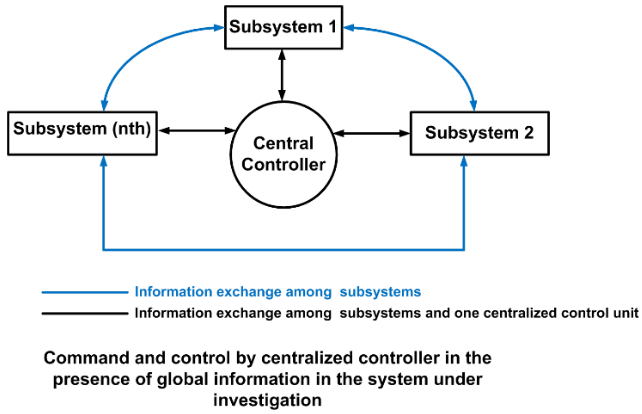

FIGURE 16. Centralized control in MG.

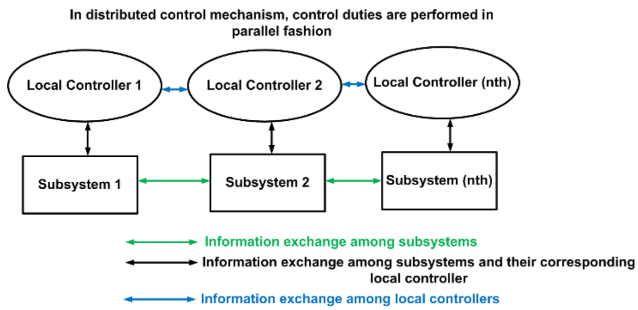

FIGURE 17. Distributed control in MG.

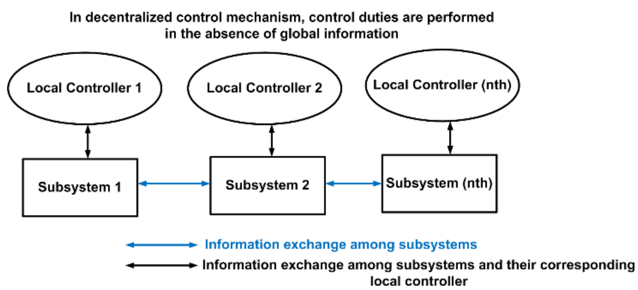

FIGURE 18. Decentralized control in MG.

among distributed agents [224], and figure 18 presents the decentralized control in MG.

Thus, distributed intelligence-based system (multiple interacting agents), control scheme, known as a multi-agent system or distributed control, is one of the most prominent and viable solutions for advancing MG control. This also served as the key catalyst behind the huge inclination of recent research literature toward this control strategy. Figure 19 illustrates the time scale and complexity related to three levels of MG control [191].

The energy management system in MG involves control software and is achieved by considering the variability of DERs, operational modes of MG, and minimal required cost [192], [193]. Therefore, MG energy management revolves around the comprehensive automated system, which is aimed at optimal scheduling of resources (energy generation and storage) and is based on information technology and control optimization techniques [194].

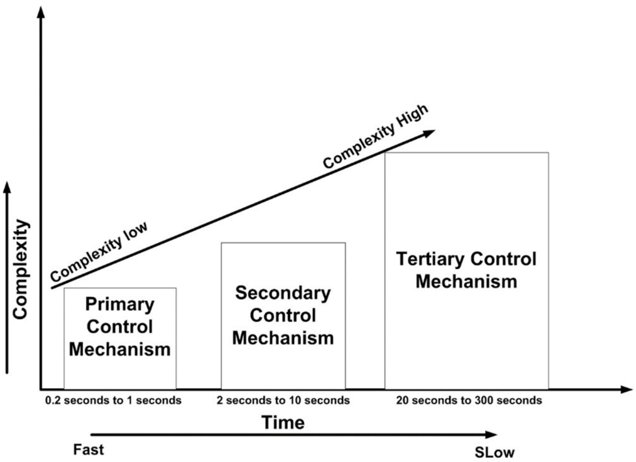

FIGURE 19. Time scale and complexity of hierarchical control in MG.

Figure 20 presents some classical methods for energy management and some objective functions defined for power systems [37], [195].

Authors in [196] illustrate a method based on linear programming to solve the cost function related to the technical and economical operation of DERs and peak loads. They used HOMER software to perform simulations based on a general algebraic modeling system (mixed-integer linear programming). They demonstrated the advantage of this programming approach for managing the volatility and intermittency in MG. A genetic algorithm-based control strategy for optimally managing the hybrid MG (which includes heterogeneous resources such as RER-based DG units, AC generators, and fuel cells) is proposed in [197]. The objective function of this research study is to minimize the cost of operation by storing the excess generated energy in batteries or hydrogen form. Energy management based on a hybrid approach of dynamic and mixed-integer non-linear programming for grid-connected MG is presented in [198]. The constraints involved in this study include battery storage and power flow, and the authors used the offline mechanism for historical data. The paper concluded that this approach may be feasible for multi-MG scenarios simultaneously.

Another interesting study based on a multi-agent system developed in the Java platform during host grid outage conditions is presented in [199]. The objective function is to minimize the operating cost while considering the randomness of critical loads, price variation of the host grid, and the intermittency of DERs. They used a differential evolution algorithm. A multi-objective stochastic scheme for hybrid MG with the objective of minimizing the system losses and operating cost using weighting sum (integer linear programming) is demonstrated in [200]. The authors solved the scheme and tested it on the IEEE 37-node system.

A two-layer Model Predictive Control (MPC) based energy management strategy for MG by incorporating the degradation costs of batteries and supercapacitors for accurate assessment of operating cost is investigated in [201]. This proposed scheme used a two-layered MPC approach for hybrid MG. The novelty of this research work is the inclusion of the degradation costs of the storage system. An Artificial Intelligent based technique using CPLEX algorithms (by IBM) for hourly economic dispatch during grid-connected mode is presented in [202]. Similarly, authors in [203] used fuzzy logic intending to minimize the deviation in grid power while maintaining the state of charge of the battery storage system.

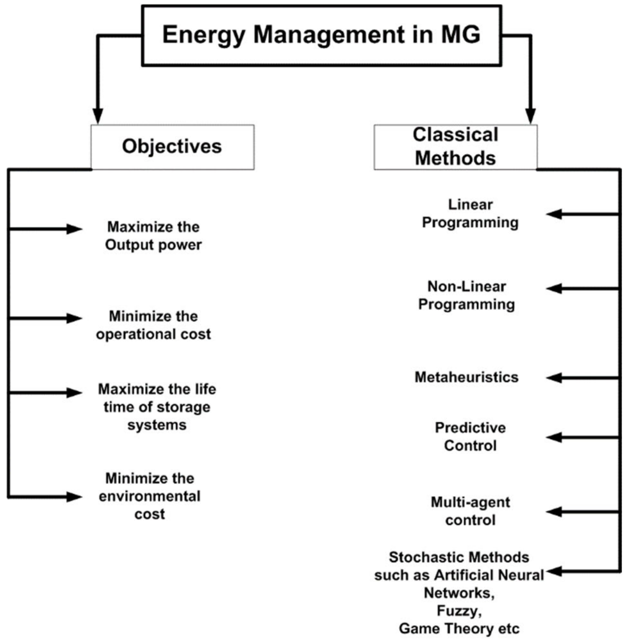

FIGURE 20. Some objectives and classical energy management methods for MG.

Authors in [204] proposed the most optimal and economical configuration for islanded MG incorporating a lithium-Ion battery storage system, using various combinations of control schemes. To evaluate the performance and longevity of the batteries, advanced models based on electrochemistry are used in this study. Furthermore, optimization techniques used in MG can be mono or multi-objectives depending on the optimization problem, such as minimization of cost-fuel, maintenance, operation, storage- and minimization of emissions or unmet loads. In literature, most authors used game theory-based schemes for solving conflicting objectives, stochastic programming for multidimensional objectives, and metaheuristic techniques for multi-objectives, constrained, and nonlinear problems. Table 5 illustrates some of the optimization methods used in MG with their objectives and constraints.

V. CROSS-SECTORAL ANALYSIS

A. CYBER-PHYSICAL MICRO-GRID

The operations of DERs, Storage, and load in smart and power electronics dominated MG are tightly coupled to the proper functionality of cyber systems. This dependence arises because the electrical components of the MG are interconnected by communication and information technologies. Therefore, smart MG can be considered a typical cyber-physical network dominated by power electronics. This cyber-physical system of MG is sub-categorized into four main layers, such as Physical (transformers, loads, generators, power converters, and circuit breakers), Measurement (sensors, actuators, measurement devices), Communication (switches, routers, communication devices), and Management (central control and management of MG). Therefore, smart MG is a complex structure consisting of distributed controllers, power converters, electrical components, actuators, sensors, and coordination, and interfacing among these components requires precise and timely communication/data exchange. Thus, this results in several issues and challenges that need special attention in research and development. Generally, the challenges involve communication infrastructure reliability, mass data/information processing and handling, data safety, the requirement of distributed computational technologies, and cyber security.

Precisely, in such types of cyber-physical systems, any corruption or delay of information may jeopardize the system's stability and safety. The recent proliferation of RER based DG units, smart storage, and load demands more coordination and a reliable cyber system. Some examples of cyber-attacks resulting in massive outages are Italy's (2003) blackout affecting around 56 million customers, Arizona's (2007), affecting 100,00 consumers, Florida's outage impacting almost 1 million consumers, and Ukraine's 2016 blackout. In MG, cyber-attacks may have devastating effects regarding the transient and steady-state stability of the system, especially in the Islanding case, as a consequence of low Inertia. Similarly, in the case of hybrid MG architecture, any cyber attack in any sub-domain (DC or AC sub-sectioned MG portion) will affect the stability of the other side. For example, a cyber attack affecting the voltage stability of DC MG (sub-sectioned) will have a greater impact on the frequency stability of the AC side of hybrid MG due to an interlinking power electronic converter. Most of the literature studies about cyber attacks revolve around the smart grid, therefore, considering the roadmap of future distributed and smart power systems, more attention of the research community is foremost in the near future toward the MG security domain. A recent survey on cyber-security within the MG paradigm can be found in [216]. In this review article, various construction methods of false data injection, defensive strategies, recent projects, and protocols/standards are discussed comprehensively.

B. POWER CONVERSION

MG requires proper power conversion to interface with the electrical system, which is achieved by incorporating power electronic converters for RER-based DG units and some high-frequency AC power sources (like microturbines). The important role played by inverters includes frequency and voltage stability during the Islanding condition of MG. Similarly, these inverters greatly facilitate the black start strategies [217]. Another critical device assisting in the synchronization and Islanding of MG is the static switch (connect/disconnect) which can respond quickly to fault conditions such as under/over frequency, under/overvoltages, and directional overcurrent. The interfacing between MG and the host grid can be performed using converters (direct current coupled) in synchronous or asynchronous AC connecting mode. Due to the back-and-forth power conversion losses of up to 15% of power generation, DC-only MG strategies are also proposed in the literature to avoid the losses of DC-AC-DC conversions. Additionally, DC MG has substantial abilities of simple plug-and-play, fault localization (via blocking diodes), and simple control and synchronization (less harmonic and zero reactive circulating currents) [218]. However, the lack of DC appliances and the requirement for large AC-DC power converters are some of the challenges to overcome before implementing all DC MG strategies in their real sense [2].

C. CONTROL

In order to maximize the economic and environmental benefits while locally balancing the load, MG requires special control strategies and delivers several functional requirements. These requirements include presetting MG as a single self-organizing entity to the utility grid (frequency control like a synchronous machine), keeping the power flow according to line ratings, regulation of frequency and voltage during the isolated mode, resynchronization, smooth Islanding, and maintaining energy balance [219]. MG can be controlled in the hierarchy of three levels like the conventional grid, comprising primary and secondary control layers (voltage/frequency control) either under the command of the main controller of MG in a centralized manner or in a decentralized way. The tertiary level is mainly concerned with the economic dispatch and overall optimization of MG. The recent inclination of the research in the literature is towards adding intelligence for optimizing MG operations and ensuring enhanced market participation [2].

D. STORAGE SYSTEM

Most of the generation resources are based on RER in MG and lack the inertia and the diversity associated with a load of a larger geographical area, therefore, a buffer in the form of the storage system is critical for mitigating the imbalances of power generation and demand. Thus, the development of storage technologies incorporating electrical, thermal, and mechanical systems may potentially contribute to the prevention of faults in MG. Additionally, storage technologies provide many ancillary services as well such as voltage support, load following, peak shifting, and spinning reserves [2], [220], [247].

E. GOVERNANCE ISSUES

The absence of a clear legal identity for MG is one of the biggest challenges in achieving regulatory certainty for making MG bankable. This legal issue arises due to uncertainties

TABLE 5. Various optimization techniques in MG.

Ref	*Technique*	*Objective function*	*Constraint*	*Comments*
[205]	MILP	Minimization of total operating cost (a) Day ahead (b) Annual cost including a battery storage system	Battery Generation	Degradation cost is not included
[206]	MINLP	Minimization of operational costs for various Distributed Generation Units	AC/DC/Converter's power Generation Units Power	The emission cost associated with biomass-based DERs is not considered. Similarly, no storage system is included in this study
[207]	PSO	Minimization of total cost and carbon footprints i.e. economic vs. environmental analysis	Generation Units Power Power exchange with the host grid Storage units charging/discharging Balance of supply and demand	The emission cost associated with generation units is not included
[208]	ABC	Minimization of total operating cost of Islanded MG	DERs (dispatchable/non-dispatchable) Storage system Power balance	Mathematical formulation complexity and emission cost associated with microturbines are not included.
[209]	Fuzzy	Minimization of operating cost, Maximization of renewable energy resources, maintain voltage and frequency within MG	Load (Battery) Power balance Generation Units power	Battery degradation cost is not included
[210]	AFSO	Minimization of total operational cost, while meeting the demand and storage constraints	Host Grid power exchange Power balance Storage system Generation Power	Degradation cost is not included
[211]	BFA	Minimization of total operational cost of the MG	Storage Units Generation Units cost DERs, Power balance	Fast convergence but without considering the power loss of the system
[212]	DYRU	Minimization of operating cost	Battery storage Power balance	Battery system cost and degradation rate are not included.
[213]	MAS	Improving the efficiency and reliability of MG	Battery system charging/discharging	Several layers of coordinated control, thus a highly complex approach.
[214]	GT	Minimization of operating cost	DG Units Power Balance Conventional Generation Units power The power exchange between MG and the host grid	Minimize fuel cost but emission cost is not considered
[215]	MDP	Minimization of operating cost over a specified time horizon	Gas Turbine Emission and capacity	Linear model but with a limited number of combinations.

Abbreviations used in Table V:
MILP= Mixed Integer Linear Programming, MINLP= Mixed Integer Nonlinear Programming, PSO= Particle Swarm Algorithm, ABC= Artificial Bee Colony, AFSO= Artificial Fish Swarm Optimization, BFA= Bacterial Foraging Algorithm, DYRU= Dynamic Rule, MAS= Multi-Agent System, GT= Game Theory, MD= Markov Decision Process

regarding whether the MG is an oversight subject for the state regulatory agency or considered as an electrical distribution utility and does the existing legal framework is sufficient to govern the generation, distribution, sale, and purchase of MG electricity. The reports about MG in the context of the existing legal framework can be found in [47], [221], and [222]. Furthermore, this legal issue stemmed due to the lack of standardization for connecting DERs with the grid, and the connection requirements vary from utility to utility greatly. However, the IEEE approved standard 1547.4 in the year 2011, which covers protection, communication, power quality, control, and functionality of MG (Islanding, Transition, Re-synchronization), phase angle, voltage, frequency specifications, and safety considerations [2].

F. PROTECTION

Protection devices designed for conventional passive power systems demonstrated slow/inactive responses to faults for active networks like MG. Also, due to overcurrent variation associated directly with two modes of MG operation (Island/Grid-Connected), the single-setting relay protection approach fails to protect against faults. Furthermore, the inclusion of DERs perpetually changes the fault current and direction in MG. The application of wide-area monitoring and protection system in MG demands a very high speed of information processing for which fiber optics and WiMAX technology are deployed to enhance the protection of MG. Moreover, protection devices like solid-state transformers also significantly impacted the efficiency of the protection system within MG. Thus, the implementation of cost-effective, reliable, and secure communication is foremost for the protection of modern power systems [188], [241], [242], [243].

G. POWER QUALITY

MG active/reactive (PQ) power quality is strictly and greatly affected due to the presence of DG units, non-linear loads, switching devices, and sensitive power conversion equipment. Advanced control strategies are a highly desirable and most important aspect of MG in enhancing the PQ of MG and the reliability of the system. During the Islanding mode of operation, MG must be able to perform under non-linear load degradation and unbalanced components because of the lack of voltage and frequency support of the host grid. Therefore, during the isolated operational mode, each DG unit within MG needs to supply a certain amount according to the total power-sharing mechanism. Issues arising during power-sharing include dependency on the line characteristics (impedance), voltage deviations, harmonic distortions, current sharing, and accuracy [3].

The emerging concept of Peer to Peer (P2P), energy i.e., energy trading/sharing, can assist in decentralizing the electricity market. The underlying concept in P2P is that in the absence of any centralized utility, consumers (among consumers) can sell or buy excess power generated via renewable energy resources or any other generation sources. This may result in the efficient use of renewable energy, ultimately reducing carbon footprints and overall energy costs. In order to ensure secure and reliable transactions among consumers in the P2P concept, Block Chain platforms can be used. This technology ensures fairness and prevents fraud by allowing decentralized and temper-proof transaction records. Furthermore, this technology also enables self-executing smart contract concepts in which the agreement (on terms) between various parties may be enforced automatically. Consequently, this may eliminate the need for intermediaries by smartly simplifying the energy trading process.

Advanced energy management systems incorporating machine learning and artificial intelligence-based algorithms can manage and monitor the power flow among consumers to enable real-time emerging trading. These smart algorithms are used to predict electricity demand and manage the balance between power supply and demand. Therefore, P2P enables the real-time trading of electricity compared to the centralized (traditional) electricity market, which may lead to excess or shortage during certain demand periods.

Moreover, the P2P energy concept furthers energy security in MG by increasing its resilience in the event of power outages/disruptions. Additionally, this concept can foster a sense of democratized MG, i.e., sense of community engagement and ownership, and enhance the decarbonized grid concept by imparting a greater sense of adaptation and awareness about sustainable/green energy practices [248], [249], [250], [251].

H. INFORMATION AND DATA MANAGEMENT

Improper control of MG leads to the instability of the system due to a lack of proper management of energy and power balance. Consequently, effective coordination and communication are required to analyze, stabilize and monitor the MG at different hierarchical levels. Therefore, communication technologies deployed in MG must be secure, cost-effective, reliable, have good transmittable range, have high bandwidth, and have fewer repetitions. Traditionally wired communication technologies are deployed due to their advantages, such as reliability and high security, but the inclusion of DERs entails a very high cost due to the complexity of the MG system. Thus, a distinct group of wireless technologies has been implemented in MG in recent years to provide decentralized and reliable communication. The poor performance of communication technology in MG may limit the MG from achieving service quality and energy efficiency and can potentially damage the whole system [3], [244], [245], [246].

Similarly, certain parameters such as frequency, active/reactive power, phase angles, voltage magnitude, root mean square and state of charge of storage systems must be monitored and controlled in MG. Therefore, proper communication and control are required at the local controller level of each DER unit for updating the information. Conventional methods of collecting data via serial ports demonstrated many shortcomings in order to serve multiple users and may cause severe instability issues in MG. Thus, modern communication infrastructure incorporating wireless technologies is widely used in MG due to its suitability for remote areas, low installation cost, and high flexibility in data transfer. So, the increased penetration of wireless technology will greatly assist in the improved proliferation of RER based DG units in MG [3].

I. SYNTHETIC INERTIA

The inclusion of RER based DG units not only resulted in some degree of uncertainty and intermittency but also introduced the issue of low inertia in MG. This further adds dimensionality to the control and operation of MG. This low inertia, in turn, may severely compromise the frequency stability of the system. In conventional power systems. Rotational inertia is associated with both minimum frequency (nadir) and rate of change of frequency. Therefore, in MG, frequency deviations are inevitable. Thus, in order to regulate the frequency, various soft solutions/ control algorithms have been proposed and implemented for power converters in MG. In literature, these strategies are referred to as synthetic/ virtual that mimics the conventional synchronous machines to impart the necessary inertia in the system. The generation units controlled by this approach are named synchronverter or virtual synchronous generators. Most of the research studies in the literature regarding these virtual machines revolve around centralized control approach compared to distributed control methodologies. Additionally, for all DC-MG, very few research studies regarding synthetic inertia are found. The virtual capacitor concept is analogous to virtual inertia is presented in some studies in order to avoid the inevitable voltage variations in DC-MGs [224]. Additionally, inertia estimation is also very crucial for system reliability. Therefore, the authors in [225] comprehensively provide an overview of inertia estimation and its forecasting challenges. Intelligent fuzzy logic based synthetic inertia control scheme is proposed in [226]. The proposed control strategy demonstrated 87% improvement in nadir (low frequency) and rate of change of frequency responses. Furthermore, the robustness test is validated by implementing various case studies for the aforementioned control policy [226]. Researchers in [78] investigated the interplay of frequency containment and synthetic inertia, and their results demonstrated the challenging nature of synthetic inertia control as a consequence of its derivate (dynamic) nature. An extensive review of the inertia in power systems, incorporating the proposal of averaged inertia estimation for various regions, is illustrated in [227]. This paper provides a significant level of information regarding inertia and frequency control schemes in modern RER based power systems.

J. ENVIROMENTAL AND ECOMNOMIC IMPACTS

MG can have several environmental and economic cross-sectoral impacts. Various environmental impacts include reduction of greenhouse gas emissions, improved air quality, reduced reliance on fossil-based fuels and land use impacts etc. Utilizing renewable energy resources such as solar and wind can greatly assist in reducing the harmful environmental impacts of electricity generation. Similarly, renewable energy resources help to improve air quality because these generation resources do not emit air pollutants such as particulate matter, nitrogen and Sulphur oxides. These pollutants are mostly associated with respiratory diseases and other negative health impacts. Furthermore, the power generation from renewable energy sources reduces the negative environmental impacts associated with the extraction and transportation of fossil fuels that, include natural gas and coal etc. However, MG can also negatively impact the environment, as in the case of power generation from biomass sources may impact land use negatively. The requirement of large amounts of land utilization for feedstock production can, in turn, cause deforestation and other such negative environmental issues. Therefore, it is a crucial task to carefully consider the environmental impacts of MG in order to ensure its positive environmental impacts [233], [234], [235], [236].

Similarly, MG can have various positive and negative economic impacts that include reduced energy costs, enhanced energy security, improved job market, and upfront and maintenance costs. MG can greatly reduce the energy cost by reducing the need for expensive infrastructure, such as transmission and distribution costs over time, as a consequence of their independence on fuel costs etc. Alternatively, the improved energy security provided by MG can further reduce the negative economic impacts associated with power disruptions and outages. Moreover, the installation and maintenance cost of MG may create new job markets in the energy sector. However, the aforementioned cost and higher upfront cost of MG infrastructure than traditional power grid can make MG less attractive and feasible for communities with limited financial resources [237], [238], [239], [240].

VI. FUTURE RESEARCH DIRECTIONS

The deployment of MG in electric power systems results in different issues. Therefore, further investigation of emerging electric networks such as MG, considering various aspects, can greatly enhance the researcher's accuracy and speed. Various issues of MG have been investigated by researchers in recent years, and several are also presented in this survey. However, some aspects related to MG need to be investigated more, and therefore, the following are some of the selective and important suggestions for the further technological development of MG.

a) Relevant to networked MG, an improved coordination framework incorporating effective control, optimization, regulatory approaches, revised grid codes, and tariff schemes required immediate research focus.
b) Control strategies for power converters, especially for grid-forming inverters during the dynamic mode of operation of MG, need more in-depth attention from the research community. Currently, research about

synthetic inertia in the form of virtual synchronous machines has been performed, but their capabilities are not universal.

c) Advanced ride through coordination strategy is required for protection systems to accommodate the topological changes or power flow patterns due to the huge sensitivity of the inverter controls and their unwanted tripping.
d) The novel concept of mobile DER/DG units may add dimensionality to the MG by supporting the supply and demand (load restoration) objectives. Thus, research in this domain is required.
e) More research and simulation/forecast platforms (parameters include energy demand, weather conditions, energy generation, equipment performance, electricity pricing, load profile and regulatory changes) are required for long-term planning and network configuration, such as placement of switches etc.
f) The incorporation of data analytics with control, especially during emergency/faulty conditions (when systems observability and state estimation is degraded) needs special attention.
g) To enable peer-to-peer energy exchange in MG, interconnection benchmarks, and agreements must be established.
h) To reduce the computational burden of energy management in MG, the concept of distrusted energy management may be applied to handle large data and reduce the processing requirements.
i) Further research concerning the storage system of MG incorporating the degradation models and real-time operating conditions is required for accurately achieving the optimal energy management in MG.
j) Similarly, more research in lithium-Ion-based batteries as an alternative to some existing lead acid batteries may help greatly in managing and enhancing the buffer (storage system abilities) in MG.
k) Load participation with the help of distributed control mechanisms is highly relevant for further research to focus especially with the inclusion of electric vehicles and other controllable/smart loads. This research domain can also positively impact the grid by supporting the whole system via demand side management programs.
l) Overcoming the inherent issues of data and packet loss and delays in communication will help in the prevention of cyber-attacks, thus, this research area is also an important part of future directions.
m) Most of the literature found about the stability of MG revolves around the convergence of control systems deployed in MG. Therefore, this area of MG is still an open question, thus more research about the stability of MG incorporating overall stability parameters such as data loss, error, delays, weak natured inverters, and exchange of information is required.

VII. CONCLUSION

This review highlights the different transdisciplinary and key enabling technologies for MG, its architectures, control, communication and their advantages and disadvantages, generation and storage systems, load classification, and protection mechanism to provide a concrete overview of the future MG system. Moreover, this survey also investigated MG optimization and energy management to demonstrate their contribution to the stability of the system by adjusting various system parameters.

Energy storage and load classification and their characteristics are discussed in detail with statistical tabular forms to illustrate their contribution in mitigating the impacts introduced due to the fluctuating (generation) nature of RER based DG units. Furthermore, tabular representation demonstrated the current and recent trends in the research community about the MG. This paper also analyzed the networked MG concept with fixed/changeable electric boundaries that can add effective resilience and robustness to the MG structure. This survey also highlights several factors, possible solutions, and challenges of next-generation MG that may help researchers and industries in enhancing the existing MG.

Thus, the key contribution of this rigorous review is the comprehensive analysis of the latest developments, current status, impacts, and future opportunities, which are aimed at providing a complete idea of the smart MG network. Consequently, due to the cross-disciplinary nature of MG, the discussion section with cross-sectoral analysis has been reviewed along with its limitations to reinforce the main content and outcome of this study.

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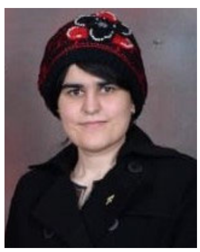

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