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TOPICAL REVIEW

Hybrid AC/DC Microgrid: Systematic Evaluation of Interlinking Converters, Control Strategies, and Protection Schemes: A Review

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ABSTRACT Hybrid AC/DC microgrid architecture is emerging as an interesting and attractive approach since it combines the prominent benefits of both AC and DC networks. In Hybrid Microgrids (HMGs), AC and DC networks are interconnected with each other through power converters. Therefore, power converters play a very important role in HMG operation, as their functionality is not only limited to interconnection but also provides power flow control and improves the power quality through different ancillary services. Moreover, due to intermittency of Renewable Energy Resources (RESs), synchronization, load variation, availability of both AC and DC networks, etc., the controllability of the power converters, power management, and protection become very complex in HMG. This paper initially provides a comprehensive review of different interconnection methods and then presents an overview of different control strategies for HMG and Inter-Linking Converters (ILCs). Moreover, power management in different operating modes, including mode transition, is discussed in detail. This paper also provides a critical assessment of the available protection challenges of HMG and provide a comprehensive review of different available protection schemes and devices is provided. Moreover, the highlights and recommendation regarding interconnection methods, control, and protection schemes are presented.

INDEX TERMS Converter control, hybrid AC–DC microgrid, interlinking converter, microgrid control, power management, protection challenges, protection schemes.

I. INTRODUCTION

In the last two decades, climate and environmental concerns and the continuous rise in electricity demand have motivated the world to integrate more and more RESs (such as wind, PV, biomass, etc.) based Distributed Generating (DG) units into the power system [1]. As RESs based power systems actively contribute in reducing energy prices, increasing the power capacity of the system, reducing greenhouse gas emissions, preventing line saturation, and improving the overall efficiency of the system [2]. However, integrating these intermittent and stochastic distributed RESs poses numerous challenges such as voltage fluctuations, system instability, economic dispatch issues, frequency deviations, etc. Moreover, the RESs based DGs have lack of inertia compared to conventional generating units [3].

In conventional power systems, the RESs based DG units are usually connected through direct connections, i.e., using passive elements such as power transformers or tie lines. Although this method has been practiced for years but it brings numerous challenges and limitations from the modularity, compatibility, controllability, and stability points of view. Hence, to cope with these challenges, a concept of Microgrid (MG) arose. An MG can be defined as an electrically bounded area of the low voltage distribution network that aggregates locally distributed generated units (DG) (PV,

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wind, etc.), energy storage elements, and controllable loads to form a self-sufficient energy system and can operate either in Grid Connected (GC) or Islanded (IS) mode [4].

An MG can be categorized into three types based on architectural topology, i.e., AC MG, DC MG, and hybrid AC/DC MG. AC MGs are the most popular and widely used architecture because the existing power network is AC and has mature control and protection systems. However, for Energy Storage Systems (ESSs) and DC loads and DGs, it requires a power conversion process, as a result, the efficiency of the system is affected. Moreover, shortage of Reactive Power (Q), synchronization complexity, and harmonic content are some of the other issues in AC MG [5]. In a DC MG architecture, the main bus is DC; therefore, DC loads and DGs can be integrated directly into the bus without any conversion process. Moreover, they provide numerous advantages compared with AC MGs, such as high reliability, simple control, do not require synchronization of frequency and phase, high power quality, etc. [6]. Although DC MGs offer numerous advantages over AC MGs but the existing power network is AC. Hence, it is not feasible to build a new DC power system network infrastructure as it consumes time and money; therefore, AC power networks are still preferable. Furthermore, due to the integration of different natures of DGs, loads, and ESSs, the individual use of AC or DC networks requires a lot of conversion processes. Hence, to cope with these challenges, the best alternative approach is the hybrid AC/DC microgrid, which comprises both AC and DC networks [7].

In HMGs, both AC and DC MGs are interconnected with each other through ILCs; therefore, they enjoy the advantageous features of both AC and DC networks simultaneously. Hence, direct integration of ESSs, DGs, and loads is practically achieved in HMG with a reduced number of conversion stages, thus reducing the overall cost and enhancing the overall efficiency. Some other advantages an HMG offers are enhanced systems' reliability and stability, high power quality, carbon reduction, reduced harmonic contents, increased transmission capacity, etc. [8]. Moreover, just like AC or DC MGs, HMGs also have the capability to operate either in IS mode or in GC mode. In a GC mode, an HMG gets the voltage phasor support from the utility grid. However, in case of IS mode of operation an HMG did not get any support from the UG, therefore, the operation of an HMG in IS mode is more complicated than in GC mode. In IS mode of operation, ILC is responsible for performing all the control functionalities and managing generation-demand management [9]. In GC mode, an ILC is responsible for regulating a DC bus voltage and ensuring an appropriate power transfer between the HMG and the distribution network. Moreover, due to AC and DC bus synchronization requirements, the architecture of HMG becomes more complex than that of independently operating AC or DC MG [10].

Although HMG offers numerous benefits but at the same time there are numerous technical challenges that need to be tackled such as ILC control, power management, power quality, stability, etc. To cope with these challenges numerous researchers have conducted a lot of work which are comprehensively discussed in numerous review articles such as stability investigation [9], fault-tolerant control [10], ILC topologies [11], control of ILCs [12], control of HMG [13], Power Management (PM) and power quality [14], protection [15], etc. Among these different technical challenges in this research work, a main consideration is given to the interconnecting techniques of AC and DC sub-grids in an HMG system, control techniques for interconnected converters and HMG are presented. Moreover, different protection challenges of HMG are presented and different schemes that are used to overcome these challenges are discussed. Moreover, as HMG is an emerging field; therefore, most of the review papers presented in state-of-the-art literature mainly focus of either AC MG or DC MG while very limited consideration is given to the Hybrid AC/DC MG.

Compared to the proposed work, the work published in state-of-the-art literature have numerous deficiencies such as in [9], the authors presented the configuration and classification of MG. Moreover, the authors also provide a detail discussion regarding the control and stability of individual AC and DC MGs. Although, some discussion regarding the control of HMG and ILC is presented but they are very limited. Moreover, this work also lacks to discuss different interconnection methods and protection schemes for HMG. In [10], the authors present the architecture, modelling, and control strategies for HMG. Moreover, different types of faults are highlighted and present different fault tolerance mechanisms for individual AC and DC MGs. In this work, a generalized concept of control of HMG is provided while it lacks to discusses different control strategies for HMG and ILCs. Moreover, it also lacks to present different protection challenges and schemes for combined AC/DC HMG. The authors in [11] provide a detailed discussion different control strategies for HMG and ILC, however, a main consideration is given to the individual control of AC and DC MGs. Moreover, this work also discusses the different operating modes of power converters and present a generalized concept of ILCs, however, a detailed classifications of ILCs and other interconnecting methods are not presented.

The authors in [12] provide a comprehensive review on different interconnecting techniques of AC and DC sub-grids and control of HMG. However, this work lacks to provide any explanation regarding the control of ILCs and protection of HMG. Moreover, it also lacks to provide any classification of MG and operating modes of power converters. The authors in [16] provide a detail discussion on different techniques used for interconnecting AC and DC sub-grids. Moreover, different control strategies for ILC are also discussed. Although this review paper provides a clear understanding of ILC topologies and control but the control and protection of HMG are completely ignored. In [17], a main emphasis is given to the control of HMG and PM; moreover, a comparative discussion of various control objectives of hierarchical control structure is also provided. Furthermore, a generalized concept of ILCs is presented, however, this works lacks discussion of different interconnecting methods and their control. Moreover, it also lacks to provide any protection challenges and protection schemes for HMG system.

In [18], the authors provide a comprehensive review on control strategies for ILC and HMG. Moreover, it also discusses PM in different operating modes. However, this work lacks to discuss different interconnecting methods and protection of HMG system. The authors in [19] provide a detailed discussion on the characteristics, classification, and components of MG, along with the operational, power quality, and communication challenges of an HMG. Moreover, different optimization techniques and control strategies for HMG are discussed. However, this work lacks a discuss any interconnecting method, control of ILC, and protection of HMG. Similarly, the structure, challenges, optimization techniques, and control of HMG are discussed in [20]. However, the authors did not provide any discussion about interconnecting methods and protection of HMG.

The authors in [21] provide a detail description of different configuration of HMG and compressively discuss different protection challenges and schemes. However, this work lacks to describe any interconnecting method and control of ILCs and HMG. In [22], the authors provide a comprehensive review of different protection challenges and their solutions for individual AC and DC MGs, however, very little discussion is provided related to the protection of HMG. The authors in [23] provide a detailed discussion on the control and power management in HMG but it lacks discussion but interconnecting methods, control of ILCs, and protection of HMG. In [24], a detail discussion about different control strategies applied to HMG is provided but to lacks to discuss the ILCs and their control, power management in HMG, and protection challenges and schemes. The authors in [25] and [26] provide a comprehensive review on the control strategies for individual AC and DC MGs while very limited consideration is given to control of HMG. In [27], different control strategies for HMG are comprehensively discusses along with the power management techniques. However, the authors did not provide any discussion about the interconnecting methods and protection of HMG. The authors in [28] presented a detailed classification of MG and different control strategies applied to AC, DC, and HMG. However, this work lacks to provide any discussion about the interconnecting methods, control of ILCs, and protection of HMG. A detailed comparative analysis of the above-discussed recent state-of-the-art review papers with the proposed work is presented in Table 1.

TABLE 1. Comparative analysis of state-of-art literature review.

REF	MGC	ICM	OPMPC	ILCC	HMGC	PM	PCs	PSs
[9]	✓	×	×	✓	✓	×	×	×
[10]	✓	×	×	×	✓	×	✓	✓
[11]	×	×	✓	✓	✓	×	×	×
[12]	×	✓	×	×	✓	×	×	×
[16]	×	✓	✓	✓	×	×	×	×
[17]	×	×	×	×	✓	✓	×	×
[18]	✓	×	×	✓	✓	✓	×	×
[19]	✓	×	×	×	✓	×	×	×
[20]	×	×	×	×	✓	×	×	×
[21]	×	×	×	×	×	×	✓	✓
[22]	×	×	×	×	×	×	✓	✓
[23]	×	×	×	×	✓	✓	×	×
[24]	✓	×	×	×	✓	×	×	×
[25]	×	×	×	×	✓	×	×	×
[26]	✓	×	×	×	✓	×	×	×
[27]	×	×	×	×	✓	×	×	×
[28]	✓	✓	×	×	✓	×	×	×
PW	✓	✓	✓	✓	✓	✓	✓	✓

Abbreviation: MGC: Microgrid Classification; ILM: Inter-Connecting Methods; OPMPC: Operating Modes of Power Converters; ILCC: ILC Control; HMGC: HMG Control; PM: Power Management; PCs: Protection Challenges; PSs: Protection Schemes; PW: Proposed Work; ✓: Presence of feature; ×: Absence of feature.

From Table 1, it can be concluded that the numerous review papers are presented related to interconnecting methods, control, and protection of HMG, however, in most of these works a main consideration is given to either AC MG or DC MG and very little explanation regarding HMG is provided. For instance, in [9], [10], [18], [19], [24], and [26] most of the authors classified the MG based on architecture, scenario, and source while a main consideration is given to the classification of MG based on architecture. However, in this work, MGs are classified based on control, configuration, generating source, scenario, application, size, and location. The authors in [12], [16], and [28] presented the ILCs however these works lack to explain the other interconnecting methods. Moreover, these works also lack to provide any discussion on the operation of the converters in different operating modes. Similarly, the authors in [9], [11], [16], and [18] provide a detailed discussion on ILCs control but they mainly focus on the unified control of ILCs and droop control techniques, however, the other control methods such as robust, predictive, and intelligent are not explained properly in context of HMG. The authors in [10], [21], and [22] elaborate different protection challenges and protection schemes for individual AC and DC MGs, however, very limited discussion is provided regarding a combined approach i.e. HMG in which both AC and DC sub-grids coexists. Based on the above discussion, it can be concluded that a lot of research gaps are still present in these sub-areas. Hence, the main contributions of this research work can be summarized as:

1. In this work, initially, the MGs are broadly classified into different groups based on their control, configuration, generating source, scenario, application, size, and location. These groups are further divided into many types and provide a detailed explanation of every type.
2. Different interconnecting methods that are used to interlink AC and DC sub-grids in an HMG system are explained. These interconnection methods are not only limited to single-stage and two-stage ILCs, but also include small Flexible AC Transmission System

(FACTS) devices, Solid-State Transformer (SST), Energy Router (ER). Moreover, based on the operating mode of power converters in HMG their operation as Grid-Following Converters (GFWCs), Grid-Supporting Converters (GSCs), Grid-Forming Converters (GFCs) are explained.

3. The control of HMG is discussed in a hierarchical manner in which different controllers applied to every control level to accomplish different tasks are comprehensively explained. Moreover, different control strategies for ILCs are explained which includes unified control, instantaneous power theory, droop techniques, robust, predictive, and intelligent controllers. Furthermore, different control strategies and methodologies are discussed to achieve a power management when an HMG is operating in IS mode, in GC mode, and even in mode transition.
4. Different protection challenges of HMG are identified and discussed in detail. Moreover, to cope with these challenges different protection schemes are investigated and are classified based on their protection principles. Besides, protection schemes different protection devices are also investigated.

The remaining parts of the manuscript are structured as follows: A review of the detailed classification of MG is presented in Section II. Section III explains the different operating modes of the power converters along with the different interconnecting methods used in an HMG system. In Section IV, different control structures and strategies for an HMG system and ILCs are discussed; moreover, power management in different operating modes are also described. In Section V, an overview of different protection challenges and protection schemes for an HMG system are presented. Finally, the concluding remarks are given in Section VI.

II. CLASSIFICATION OF MG

MGs can be categorized into seven different groups according to their configuration, application, location, scenario, generating source, control, and size as presented in Fig. 1, and are discussed below in detail.

A. CLASSIFICATION OF MG BASED ON CONFIGURATION

Based on the voltage characteristics and system architecture the MGs are classified in four categories, i.e., (a) DC MG, (b) AC MG, (c) hybrid AC/DC MG, and (d) networked MG.

1) DC MICROGRID

In a DC MG architecture, a main bus is DC; therefore, DC loads can be integrated directly to the bus without any conversion process. However, for AC loads, DC-AC inverters are needed for inversion to make it applicable for the AC loads. A generalized schematic of DC MG topology considering different AC/DC loads and DG units is presented in Fig. 2. The increase penetration and high development in RESs based DC DG units in recent years have accelerated

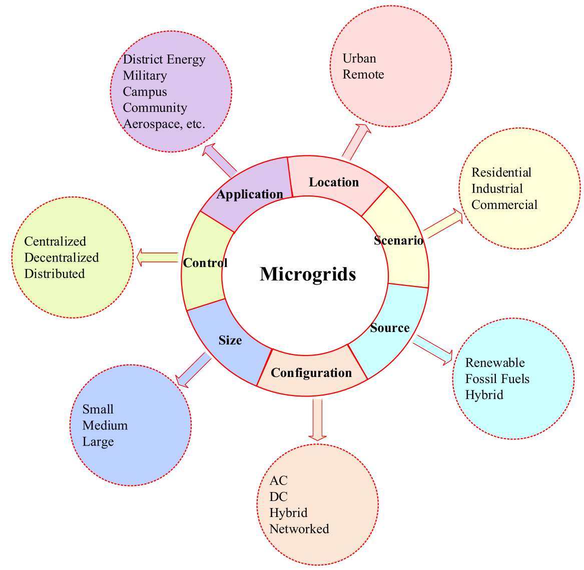

FIGURE 1. Classification of MGs.

the research in the area of DC MG architecture. In case of PV generation, DC-DC step-up converters are used to integrate the PV system with the DC bus of an MG. In case of wind power generation, AC-DC converters are used to convert the output power of wind turbines (AC in nature) to make it applicable to integrate with the DC MG.

DC MG offers numerous advantages such as (a) high energy efficiency, (b) low energy conversion losses due to less usage of power electronic converters, (c) DC based DGs can be integrated and control easily, (d) direct interconnection of Battery Storage System (BSS), (e) RESs generation and load fluctuation can be managed easily by using BSS to complete the power deficiency, (f) it is easier to dump the circulating current between RESs, and (g) simple grid integration [29]. Despite these numerous advantages there are some disadvantages of the DC MG topology such as (a) majority of the load is AC, therefore DC to AC inversion is required, (b) in a DC distribution system a voltage drop occurs as the distance from the generation increases, therefore voltage boosters are required, and (c) required an AC-DC rectifier for the AC generating units [30].

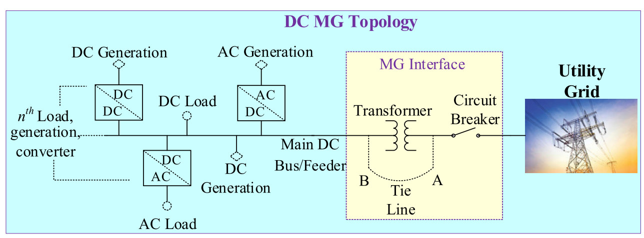

FIGURE 2. Generalized overview of DC MG system.

2) AC MICROGRID

In AC MG configuration, all the generation resources and load are connected to the common main AC bus. Based on the distribution structure, this configuration can be classified in three sub-categories that includes three phase with neutral line, three phase with no neutral line, and single phase. As the majority of the loads are AC in nature, therefore, in this configuration, AC loads can be directly fed without using any PE conversion mechanism. However, for DC loads, AC-DC rectifiers are used. Similarly, for DC power generating units such as PV, DC-AC inverters are used to make it applicable to integrate with the AC bus. Moreover, it is simple to integrate the AC MG with the UG, as the UG (conventional power system) operates AC however a phase matching between the MG and UG is required [31]. A generalized schematic of the AC MG configuration (considering different AC/DC loads and DG units) connected with the UG through circuit breaker is presented in Fig. 3.

The main advantages of AC MG configuration are (a) AC MG are connected to medium and low voltage distribution networks that enhances the power flow and decrease the power losses in the transmission line, (b) voltage stability, (c) autonomous control of Q, (d) highly efficient transformers, and (d) simple quenching procedure of fault arc current at zero crossing (highly reliable performance of circuit breaker) [32]. Beside these numerous advantages there are some demerits that are associated with this configuration such as (a) for DC loads, AC-DC converters are needed that greatly affect the system's efficiency, (b) inclusion of DC-AC inverters for integrating the DC generating DGs, (c) introduction of harmonics, [22] (d) synchronization of voltage phasor of AC MG with the UG is required that makes the management and control of AC MG is more complex than the DC MG, [33] (e) synchronization of RESs based DGs is complex, and (f) shortage of Q in case of RESs based DGs (specially PV).

3) HYBRID MICROGRID

A hybrid MG configuration consists of both DC and AC bus distribution systems. A main objective of this configuration is to minimize the number interface devices and conversion stages while maintaining the price of energy low [34]. Thus, as a result, the overall reliability and efficiency of the system can be improved. In hybrid MG configuration, the power flow between the UG and the networks is controlled by static switch and PE converters, respectively. A balance between supply and demand (i.e. load and generation respectively) determines the direction of the power flow. To interface both AC/DC MGs, in this configuration, bidirectional AC-DC converters are used. Moreover, DC-DC step-up converters are utilized for connecting the DC generated energy resources with DC main (sub-bus) in DC MG. While DC-DC step-down converters are used for DC loads, and bidirectional DC-DC converters are used for interconnecting the Energy Storage System (ESS) with the DC MG (sub-section of hybrid MG). The interlinking converter between DC and AC MGs (sub-sections) work according to the overload conditions. When an AC MG (sub- section) is in overload condition, then the interlinking converter acts as an inverter and the direction of power flow is from DC to AC MG. On the contrary, when the DC MG (sub-section) is in overload condition then the direction of power flow is from AC to DC MG and the converter will act as rectifier. Hence, in most of the literature, the interlinking converter is considered as the key converter that controls the power flow between DC and AC subsections of the hybrid MG configuration [22]. A generalized structure of HMG structure is presented in Fig. 4.

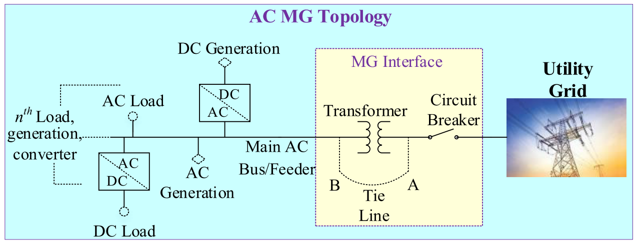

FIGURE 3. Generalized overview of AC MG system.

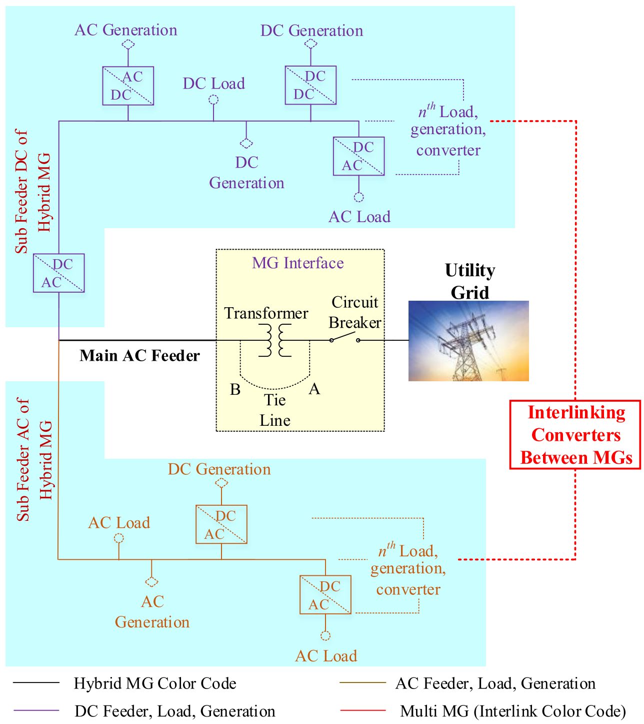

FIGURE 4. Generalized overview of hybrid AC/DC MG system.

The main advantages of hybrid MG configuration includes (a) reduced conversion stages as a result the conversion losses are reduced, (b) DG units can be tied to the DC or AC bus, (c) reliable ancillary services, (d) Plug and Play (PnP) type management of DC or AC subsection, (e) improved load support, (f) UG voltage support, (g) increased economic operation, (h) overcome the disadvantageous features of individual AC or DC MG. Beside these numerous advantages, the main demerits of this configuration are (a) the inter-relationship between and DC and AC sub-sections introduces several operational issues and makes the configuration very complex [22], and (b) less reliable compared with AC MG [35].

4) NETWORKED MICROGRID

In Networked Microgrid (MMG) configuration numerous MGs are connected with each other to improve and reliability of the system as presented in Fig. 5. In this configuration, every MG support other MGs in case system disturbance or in case of some MGs face generation deficiency. The main objective of MG clusters or MMG is to improve the reliability, stability, and reduce load shedding in distinct MGs.

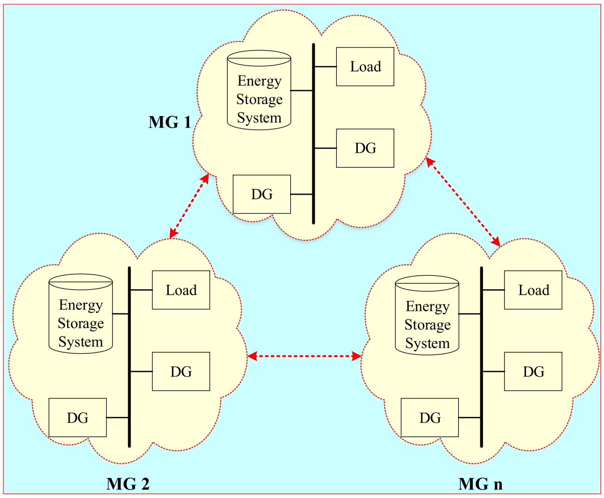

FIGURE 5. Generalized overview of networked MG system.

In MMG configuration, different MGs are interconnected into distribution feeders incorporating dynamic or fixed electrical boundaries through distributed or centralized controller. In state-of-the-art literature, a concept of the dynamic boundary is also stated as grid sectionalisation. In this, the boundaries are self-organized that are assisted by the inclusion of new RESs based DG units. While in fixed electrical boundary, the overall electrical boundary of the system is defined after the merging of different interconnected MGs. The overall or global boundary is naturally defined the PCCs and switches. Numerous MGs are clustered within fixed electrical boundaries to ensure that the load demand in balanced [36]. However, the dynamic adjustment of electrical boundaries of nested MMG is possible with the help of voltage and frequency regulation mechanisms. Hence, these fixed boundaries are flexible and operated by using switch gears that may perform as temporary PCCs for the new boundaries. Hence, this approach leads to a concept of virtual MG [37].

A concept of virtual MG is similar to the concept of virtual power plant MG but with the additional capabilities such as the incorporation of storage devices, load components, and heterogeneous generation and grid forming ability. Likewise, a concept of nested MG is close to the MMG concept, in which numerous MGs are interlinked with each other through electrical links to improve the efficacy and facilitate the power exchange [38]. In all these MMG concepts, there are numerous research challenges that are needed to address such as (a) communication problems, (b) control and management of the system, (c) information security, (d) increase the system's intelligence in order to ensure the stability and provide a reliable and un-interruptible power supply to the users.

B. CLASSIFICATION OF MG BASED ON CONTROL STRUCTURE

According to the control structure there are three types of MG; i.e., centralized, decentralized, and distributed control structure as shown in Fig. 6(a), 6(b), and 6(c) respectively. In centralized architecture, a single central controller that acts as a brain of the MG control system is responsible for performing all the control tasks. It collects all the information from different parts of an MG through wireless or wired cyber system and make the decision and supervise the controllable loads, ESS units, DGs accordingly. In a centralized control architecture, every component (DG, load, ESS, etc.) is connected with the controller independently via a separate cyber-channel, as a result, the cost and complexity of the system is considerably increased [39].

In a decentralized control architecture, each controller is designed autonomously, but all these autonomous controllers together form a network that presents an entire power system.

In this the controller only require the local information to perform the control actions therefore it in case of any communication fault only the faulty part of the system get affected. Beside these advantages, the main limitations in this architecture are poor performance during sharing of non-linear loads, sensitivity to line impendences, amplitude deviation, and inherent dependency of frequency on load. Furthermore, its effectiveness in under question in circumstances when the exchange of power required between two sub-grids [40]. One typical example of this scenario is the widespread blackout of August 2003 in North America [41]. In that accident, each DG only focused on maintaining its own subsystem stability and transferred the extra load to other DG, which made the overload more severe and eventually caused a blackout.

A distributed control architecture allows information exchange among local controllers by establishing a communication network among them. In fact, distributed control strategies can be considered as a trade-off between the centralized and decentralized control architectures as it combines their advantageous features. There are also other also other factors that motivate distributed control, such as (a) high feasibility for Plug and Play (PnP) functionality, (b) low cyber cost, (c) low bandwidth cyber network, and (d) high robustness to single point failure [31].

C. CLASSIFICATION OF MG BASED ON LOCATION

One the basis of location, the MGs can be classified into two types; i.e., urban MG and remote MG. Urban MG is established in the urban areas close to the utility system and they

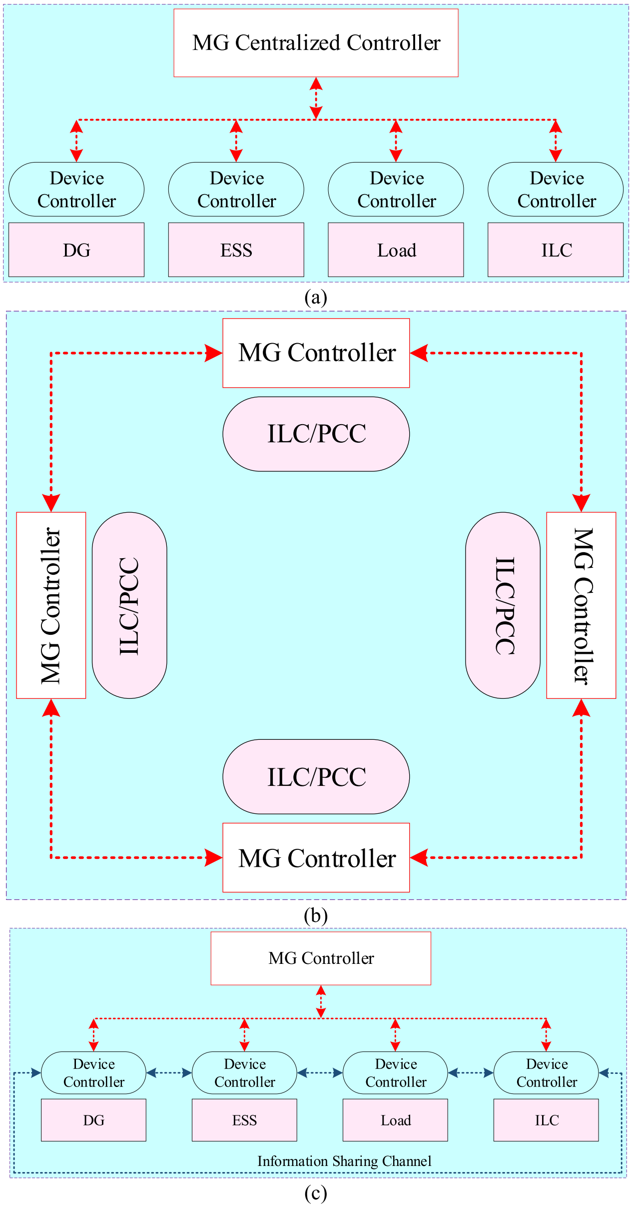

FIGURE 6. **Control architectures (a) centralized, (b) decentralized, and (c) distributed.**

follow all the rules, standards, synchronization techniques, and control strategies to maintain the high-power quality and ensure the stability of the UG system [42]. Universities, communities, hospitals, shopping malls, and offices are among the residential and commercial sectors where the where the urban MGs can be developed and implemented.

More than 1 billion of world's population living in underdeveloped and developing countries have no access to reliable or any electricity. In most of the cases, the limited electricity that is accessible to these people are generated by using expensive fossil fuel especially diesel fuel. To be more precise, for the people of remote areas, electricity is a main source for fulfilling the basic human needs. Hence, MG can be considered as the best possible solution to deliver the electricity to these areas [43]. Remote MGs combine the clean energy generation and ESS, in some scenarios provide the facility of mobile payment platforms; providing a life-line to the people, allowing the medical system to arrange the reliable services, and allowing students to study during night time. In remote MGs, the addition of RESs based DG units with the existing diesel based energy generating units, show a great potential to lower the MG operating cost and diversify the generation in island communities that mainly rely on expensive oil for energy generation (due to far away from the existing power system) [44].

D. CLASSIFICATION OF MG BASED ON SCENARIO

Based on scenario, MGs can be classified in three categories i.e. residential, industrial, and commercial MGs. A residential MG is composed of an advanced controller that combines the electricity or energy demands of the customer, regulates the DG, and coordinates with the distribution power networks. This type of MG reduces the dependency of the customer on electricity provided by the UG and also provide emergency power to the UG in case of power outage. To ensure the reliable and secure power to the industry an industrial MG is implemented. In the production process of some industries such as chemical industry, chip production industry, food industry, and oil refinery etc.; the power outage disturb the production process due to lengthy start-up times of the machineries resulting a considerable loss in revenue. The commercial MGs are usually deployed to serve a single entity such as hospitals, airports, etc. This type of MG system is usually self-sufficient and may have the ability to operate independently from the UG or may be operate in a GC mode at the time of need. By having the advantage of backup power, having the option to generate electricity from multi resources, and day-a-head energy prices, facility to connect to the UG can boost self-independency and sufficiency and minimize the electricity cost.

E. CLASSIFICATION OF MG BASED ON SOURCE

A most important and significant part in the electrical system is the energy resources or generation units. As an MG is the combination of different energy generating resources therefore to balance the demand-supply graph numerous different combinations of these resources can be used [45]. Hence, based on the sources the MGs can be classified into three categories i.e. fossil fuels based MGs, renewable based MGs, and hybrid MGs that are discussed below in detail.

In fossil fuels (natural gas/diesel) MGs, the generators are used to balance the demand-supply mismatch in the remote areas. However, the power generated from these sources have a negative effect on both the economy and environment. As the fossil fuels required to generate electricity in MGs are very expensive to transport and purchase, moreover, its transportation has its own carbon footprints. Hence, fossil fuels based MGs are not the best solution to produce electricity in today's world and researchers are exploring more sustainable and clean source of energy due to these impacts [46].

The type of MGs that are powered by RESs based DG units are known as RESs based MGs. This type of MGs usually consists of RESs and ESS (batteries). Compared to the fossil fuel based DGs, the integration of RESs based DGs has increases significantly due to sustainable and clean nature, implementation of environmental programs, low carbon emission, and green governance attitude and policies. However, beside the numerous advantages, the main disadvantages of RESs based DGs is its vast variability and volatilities in power generation due to their high dependency on meteorological factors. The intermittent and uncertain output of RESs based DGs increases the operational complexity of the MG. Moreover, the time varying energy demand also increases the operational complexity of an IS MG. Hence, to balance the demand-supply graph, an ESS is the most appealing and the best solution [47]. An overview of RESs based DG units that include its benefits, drawbacks, solution, source of origin, governance approach is presented in Fig. 7.

From Fig. 7, it can be observed that every RESs based generating units have its own drawbacks and limitations, which includes intermittency, reliability, variable output power, etc. Hence, to cope with challenges a concept of Hybrid Renewable Energy System (HRES) is arises which allows the integration of different available energy resources n but at least one of the sources must be RESs based source. Hence, this concept can overcome the limitations of individual RES based generating unit in terms of reliability, emissions, energy efficiency, and fuel flexibility. The authors in [48] proposed an HMG system in which PV, wind, micro-turbine, BSS, and fuel cell are combined to ensure un-interruptible power supply. In this method, an ANFIS based energy management system is used to provide power to the UG. Similarly, the authors in [49] proposed a system in which wind, tidal, hydrogen, and BSS are combined together. In this work, maximum power point tracking method is used to extract the maximum from the wind and tidal systems. During the off-peak time the excess energy is stored in BSS and some energy is transferred to electrolyzer where the electrical energy converted into hydrogen that can be used by the fuel cells during the peak time. In [50], a combination of PV system, BSS, and diesel generator are used to minimize the fuel cost of diesel generator and efficient use of PV based generating unit. An energy management system is developed that extract the maximum power from the PV system to meet the load demands. The extra power is used to charge the BSS that can be used during peak hours; however, a diesel generator is used to meet the load requirements when the PV system and BSS are unable to fulfil the requirements.

F. CLASSIFICATION OF MG BASED ON APPLICATION

MGs can be installed in campus to aerospace; therefore, based on application MGs can be classified into many types. Campus/Institutional MGs are usually deployed on-site generation

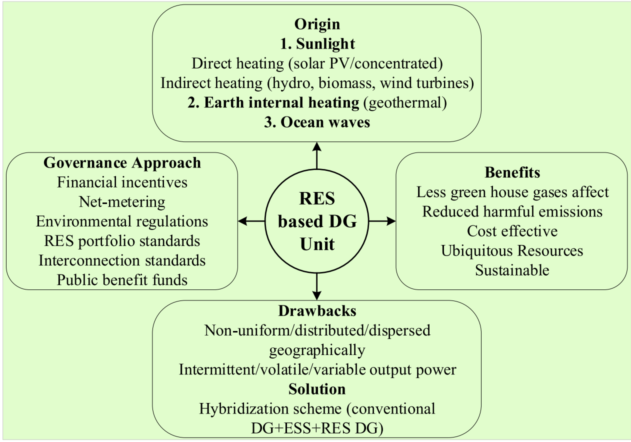

FIGURE 7. Overview of RESs based DG units.

and are specialized in Combined Cooling, Heating, and Power (CCHP) application. A community MG is supported by high penetration of RESs based DGs and are frequently installed in the developed areas to support the communities to reach the RE goals. This type of MG is limited to a specified electrical bounded region and have the capability to operate in IS as well as in GC mode. The military MGs are the small-scale electrical system that are confined to the military base camps only and are mostly operate autonomously. Island MGs are the small-scale MGs that work completely independently from the UG and generate their own power to meet the energy demands.

A reliable power system plays a significant role for the success of very expensive space mission; therefore, space MGs are designed that provide a sustainable and reliable energy to meet the demands of satellite or spaceship [51]. Similarly, in recent years, a concept of aerospace MG has gained a great importance due to its increase applications in the aerospace technology. In numerous aerospace applications such as electric aircrafts, airports etc., the pneumatic and mechanical power sources are gradually replaced by the electrical sources [52]. MGs can also be installed in ferries, ships, vessels, etc. and has the ability to work in IS mode at sea and in GC mode at port. The installation of these MGs is increasing rapidly as these MGs are affordable and the ships become more and more electrical [53].

G. CLASSIFICATION OF MG BASED ON SOURCE

Based on size, the MGs can be classified into three types, i.e. large, medium, and small-scale MGs. An MG is said to a large-scale MG when its generation capacity is greater than 100 MW and uses RESs/coal/oil or any combination of these electricity generating sources [51], [52]. Large scale MGs are capable to meet the load demands of the industrial zones site. The medium scale MGs generate electricity of medium capacity by using RESs/coal/oil or any combination of these source. According to [54] the generating capacity of these MGs is greater than 10 MW and less than 100 MW.

TABLE 2. Classification of MG based on size.

Type	Generation Capacity (MW)	Application	Fuel
Large	>100	Industrial site	RESs/fuel/coal
Medium	10-100	Industrial zone	RESs/fuel/coal
Small	10	Remote area, island, residential building, small regional power grid	RESs

These MGs have the capability to meet the energy demands of industrial zones. In a small-scale MGs, the electricity generating capacity is low and uses RESs for energy generation purpose. However, in some MGs, diesel generators are used along with the RESs or in place of RESs. A generating capacity of these MGs ranges up to 10 MW [45]. These MGs are capable to meet the energy demand of remote areas, small residential community, and residential building, etc.

The prominent features such as application, generating capacity, and type of fuel of these MGs are summarized in Table 2.

III. INTERCONNECTION METHODS IN HMG

In this section, the power converters are classified based on their operating modes and are briefly explained. Moreover, different interconnection techniques that are used to integrate AC and DC sub-grids are discussed in detail. A schematic of these categorization is presented in Fig. 8.

A. OPERATING MODES OF CONVERTERS

Based on the operation of power converters they are classified into three types, i.e., GSCs, GFCs, and GFWCs. They are briefly explained in this sub-section and their main features are summarized in Table 3.

1) GRID-FORMING CONVERTERS

In an HMG, GFCs are mainly associated with the ESS units. In an IS mode of operation, GFCs are responsible for maintaining the nominal frequency and voltage at the AC sub-grid side while maintaining the nominal voltage at DC sub-grid side. In GC mode, GFCs are responsible for Active Power (P) regulation in a DC sub-grid, while in an AC sub-grid, GFCs are responsible for regulating both P and Q. Moreover, due to accurate power regulation, these converters keep the State of Charge (SOC) of the ESS unit high, which in turn enhances the power quality (AC sub-grid) and voltage profile (DC sub-grid) [55]. Furthermore, GFCs are considered as controlled voltage sources and are operated in Voltage Control Mode (VCM) to control the voltage (DC sub-grid) or frequency and voltage (AC sub-grid) [56].

2) GRID-SUPPORTING CONVERTERS

As ESS units have a limited power reserve capacity to be absorbed or delivered, therefore, sometimes the GFCs fail to accurately regulate the pre-allocated frequency and voltage in the sub-grids. Therefore, to cope with this problem, additional ESS units or DGs are used that support the GFCs to regulate the pre-assigned voltage and frequency in the sub-grids of HMG system in IS mode [55]. These converters are considered equivalent to controller current source/voltage source having associated high/low impedances in parallel/series, respectively [56]. These converters can operate in both Current Control Mode (CCM) and VCM; therefore, in GC mode, these converters support the voltage profile (DC sub-grid) and improve the quality of power (AC sub-grid). Besides these numerous advantages, these converters offer low inertia that may affect the performance and stability of the HMG. Hence, to overcome this problem, numerous researchers have introduced and modified the concept of virtual inertia devices and virtual synchronous generators [57].

3) GRID-FOLLOWING CONVERTERS

The GFWCs are generally associated with non-dispatchable DGs such as wind, PV, etc. In case of AC sub-grid side of HMG system, the GFWCs follow the frequency and voltage

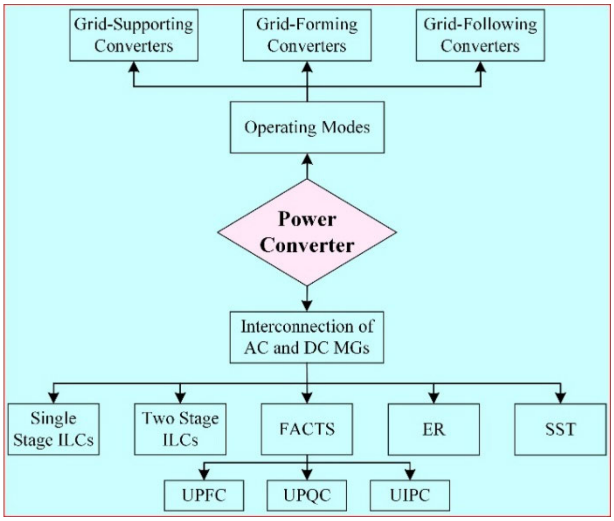

FIGURE 8. Power converters in HMG.

TABLE 3. Characteristics of different converters.

Features	GFCs	GSCs	GFWCs
Power flow control	One way	Two way	Two way
Application	IS	IS and GC	GC
Source type	Controlled voltage source	Controlled voltage or current source	Controlled current source
Output frequency and voltage	Fixed	Regulated	Sub-grid synchronization
Association	Dispatchable sources	Dispatchable sources	Non-dispatchable sources
Combination	Series	Series-parallel	Parallel
Output Impedance	Fixed	Finite	High

of the UG as a reference and inject the *P* and *Q* accordingly to achieve a unity power factor. Similarly, to attain a unity power factor in case of DC sub-grid of the HMG system, the GFWCs follow the UG voltage as a reference and inject the power or current into the UG [55]. AS GFWCs follow the reference values of UG, therefore, they are considered as controlled current source with a high impedance in parallel. These converters can be easily installed in parallel with other GFWCs; however, they are not involved in power balancing. Moreover, due to the tracking of UG values as a reference and the injection of current into sub-grids, these converters show similar behaviour in IS and GC modes [56]. However, in IS mode, the GFWCs are unable to perform their functionality without the support of synchronous generators or GSCs [58].

B. INTERCONNECTION METHODS

An HMG must include at least one DC sub-grid and one AC sub-grid, which are interconnected with each other through ILCs. These converters either acts as an inverter or rectifier depending on the direction of power flow. When an HMG is connected with the UG, then the ILCs control the voltage at the DC bus. However, when the HMG is operating in IS mode, then ILCs provide a slack bus either to DC sub-grid or AC sub-grid [59]. Different converter configurations and topologies can be used to facilitate the power exchange between AC/DC sub-grids and the UG. A selection of ILC topology mainly depends on the control objectives that are required to be fulfilled. With the advancement in technologies and desire to achieve high quality waveforms, the control objective of the ILCs is not only limited to power management; it also involves stability improvement, ESS units' coordination, control of grid current, islanded detection, etc. Hence, to fulfil these control objectives, usually, single-stage and two-stage ILCs are used to interconnect multiple DC and AC sub-grids [60]. However, by investigating the state-of-the-art literature, one can find some other alternatives that can be used instead of ILCs, such as small-scale FACTS devices, SST, and ER.

1) SINGLE-STAGE INTER-LINKING CONVERTERS

A generalized structure HMG system in which Bidirectional ILC (BILC) is used to interconnect the DC and AC sub-grids is presented in Fig. 9. A DC sub-grid may consist of PV, batteries, and various DC loads. On the contrary, an AC sub-grid consists of a micro-turbine, diesel generator, wind turbine, and different AC loads. Generally, single or three phase full bridge converter topologies are used as ILCs in HMG systems. However, due to the operational and control complexity of conventional topologies, the authors in [61] presented a BILC that interconnects the DC and AC sub-grids in an HMG system. This BILC enables an HMG to easily accommodate the ESS unit, as presented in Fig. 10. Beside the ESS accommodation, this converter topology makes the DC side more reliable, stable, and fault-tolerant. A high voltage conversion ratio Γ-Z-Source BILC to interconnect the DC and AC sub-grids in HMG is presented in [62]. Compared to conventional BILC, this converter topology is more reliable and attain high efficiency. When an HMG is operating in IS mode, then the AC sub-grid along with the Γ-Z-Source BILC are responsible for regulating the frequency and voltage.

A quasi-Z-source BILC for HMG applications has been proposed in [63]. A maximum constant boost with reduced stress on switches is achieved by this converter in both IS and GC modes. In [64], a switched boost bidirectional converter that acts as an ILC in AC/DC HMG is proposed. The prominent advantageous features of this topology include reduced components count and better stability. The authors in [65] presented a modular multilevel ILC to manage the power flow of AC and DC sub-grids. In this topology, an individual battery is connected to each of its modules, thus reducing the power exchange among the sub-grids and increasing the overall system's efficiency.

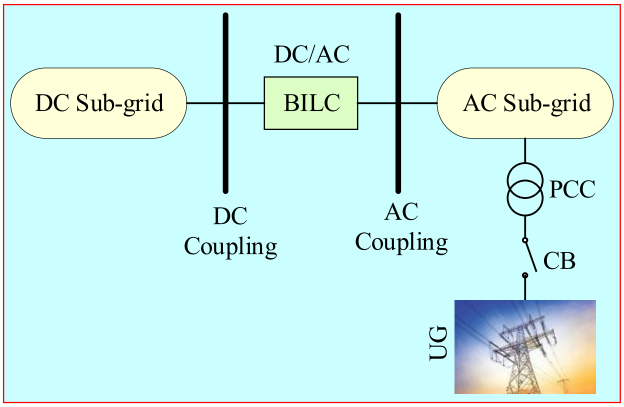

FIGURE 9. Interconnection of AC and DC sub-grids in an HMG using BILC.

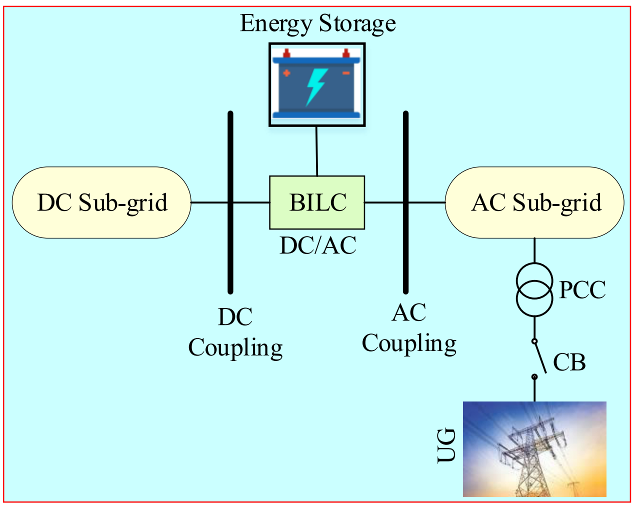

FIGURE 10. BILC connection topology along with ESS in HMGs.

2) TWO-STAGE INTER-LINKING CONVERTERS

In literature, two-stage ILCs are reported that either have a parallel or cascaded combination of different converters.

These types of ILCs increase the reliability and power exchange capability of the interconnected MGs as well as provide a greater degree of freedom in terms of control. A generalized schematic of interconnected MGs using parallel connected BILCs is shown in Fig. 11. In [44] and [66], the authors proposed a two-stage ILC in which in the initial stage, a DC-DC converter is used, while in the second stage, a DC-AC inverter is utilized. Moreover, an ESS unit is also integrated into the common DC bus through the DC port of the converter at the initial stage. A main objective of this topology is to ensure the *P*-sharing is an HMG when it is operating in IS mode. Moreover, power-sharing in this topology only depends on the rating of the source, not on their placement in the HMG. The authors in [67] proposed an HMG network configuration in which back-to-back converter uses BILC to interconnect the AC and DC sub-grids. This configuration facilitates power exchange among AC and DC sub-grids and ensures the stable operation of DC-link. A generalized schematic of this topology is presented in Fig. 12. Back-to-back converters can also be used to integrate AC MGs with different nominal frequencies, as presented in Fig. 13 [68]. In [69], the authors proposed a two-stage ILC for HMG applications. In this topology, a DC-DC half bridge converter is connected to a DC-AC inverter to improve the power quality.

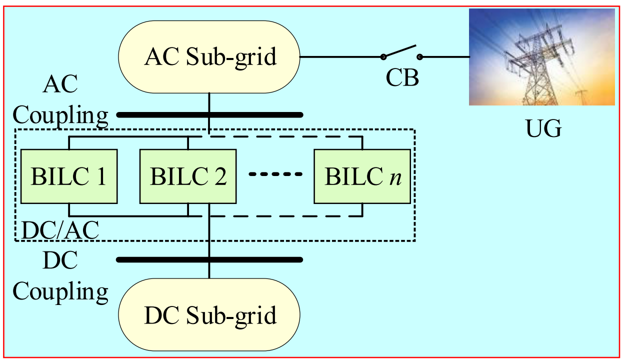

FIGURE 11. Generalized schematic of parallel connected ILCs.

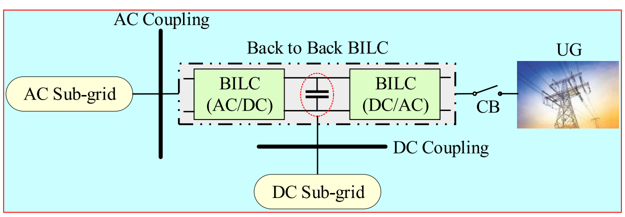

FIGURE 12. Back-to-Back BILC for interconnecting an HMG.

3) INTERCONNECTION OF HMG BASED ON ENERGY ROUTER

A generalized schematic of ER to interconnect different sub-grids in an HMG system proposed in [69] is shown in

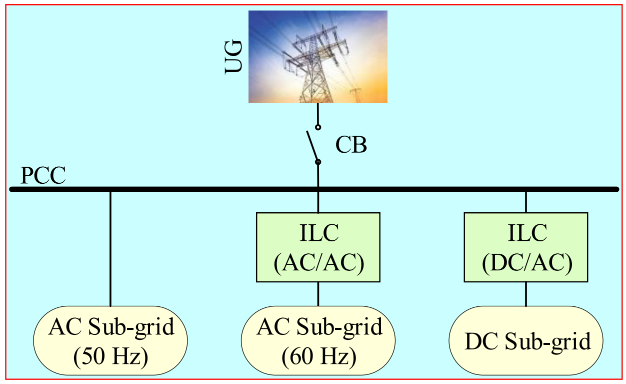

FIGURE 13. Schematic of HMG interconnected by ILC having different AC sub-grid.

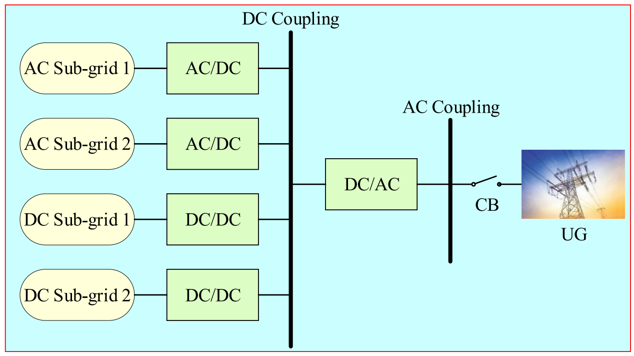

FIGURE 14. Concept of ER to interconnect HMG.

Fig. 14. From Fig. 14, it can be seen that an ER consists of numerous DC/DC, AC/DC, and DC/AC converters that interconnect sub-grids of different characteristics. The AC/DC converters facilitate the integration of AC sub-grids with different frequencies to a common DC bus, whereas DC/DC converters are used to integrate different DC sub-grids of different voltage levels to a common DC bus of the ER. Finally, DC/AC converters (rectifiers) are used to facilitate a bidirectional exchange of power between HMG and UG. A multiport ER with ESS units has been used to integrate the HMG with different generation/consumption patterns [70]. This method is used to compensate the power shortage in sub-grids when necessary. Similarly, the authors in [22] proposed a PM. strategy based on dual-loop feedback controller for an ER based HMG system. This work avoids the use of ESS units, thus results in lower costs

4) INTERCONNECTION OF HMG BASED ON SOLID-STATE TRANSFORMER

Traditional power transformers are widely used in power systems for interconnection purposes, such as the interconnection of medium-voltage lines with low-voltage lines. However, these transformers are not very feasible in HMG as they show low flexibility and less efficiency due to the addition of passive impedance into the line. Hence, in the

HMG system, SSTs are used to facilitate the integration of ESS units and DGs. The main advantage of SSTs over the traditional transformers in HMG is that they provide a low-voltage DC-link that makes the integration of ESS units and DGs very easy. Moreover, SST also includes a DC-DC converter with a medium operating frequency, which results in low cost, high efficiency, and a reduction in passive element size. Moreover, as SSTs are power electronics based devices; therefore, control features like regulation of frequency and voltage, sharing of P and Q, Q-compensation, and power quality enhancements can be easily achieved.

Numerous SST topologies have been developed for the interconnections in HMG. For example, the authors in [71] use the DC and AC links of SST to interconnect a DC sub-grid, AC sub-grid, and AC power system in an HMG system. A generalized schematic of this topology is presented in Fig. 15. In this work, the authors presented a distributed PM scheme that focuses on the DC side while regulating the charging and discharging states of the BSS. Moreover, SST in this work enables a bidirectional power flow in HMG. Similarly, the authors in [72] use an SST to interconnect an HMG having different voltage levels. In this work, SST interconnects low and medium voltage level AC buses and DC sub-grids with the main objective to show the effectiveness of SST during faults in comparison to traditional transformers. Another work in which a three-layered modular SST topology is used in an HMG system to interconnect a DC sub-grid with an AC load and power system is presented in [73]. The response of SST during the fault is also considered, and it is concluded that SST plays a significant role in reducing power quality problems.

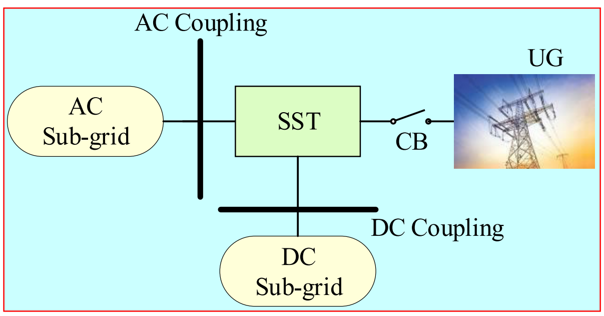

FIGURE 15. AC and DC sub-grids connected by SST.

5) INTERCONNECTION OF HMG USING FACTS

In large power systems, FACTS devices are widely used for Q-compensation, power flow control, and stability enhancement [71]. In recent years, researchers have tried to modify the model and control of the small-scale FACTS devices to make them feasible for MG applications. Hence, based on modifications, FACTS devices such as Unified Power Quality Conditioner (UPQC), Unified Interphase Power Controller (UIPC), and Unified Power Flow Controller (UPFC) are used for HMG interconnecting applications.

UPQC devices have been widely used in power systems to address power quality issues like voltage control, Q- compensation, harmonic reduction, etc. UPQC has a common DC-link that is present in between its parallel and series converters. This DC-link can be connected to the DC sub-grid of the HMG system [74]. This feature enables UPQC to be an effective device for controlling the power flow and improving the power quality. Due to these advantageous features, the authors in [75] use UPQC for interconnection purposes in HMG, a schematic of which is presented in Fig. 16. From Fig. 16, it can be seen that two ILCs are used to form a back-to-back topology, and these converters along with the series power transformer make a UPQC topology with a common DC bus that is connected to DC sub-grid. This topology enables voltage regulation, Q-consumption/injection, reduction in power fluctuations, and improvement in power quality.

A traditional Interphase Power Controller (IPC) is one of the FACTS devices that is used in large-scale power transmission lines. It is connected in series with the transmission lines, and by using phase shift transformers, it injects the voltage into the lines. The voltage injected by the IPC changes the phase and amplitude of the line current, which results in controlled power flow among AC buses. However, to make IPC feasible for HMG applications, the authors in [76] modified the traditional IPC by replacing the phase shifting transformer with converters and named it UIPC. This modification results in high controllability in power, enhances the fault protection features, enhances the voltage regulation feature, and reduces losses.

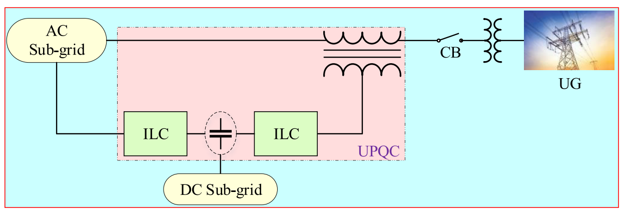

FIGURE 16. Schematic of HMG interconnected by UPQC.

A conventional UIPC presented in [76] is modified by the authors in [77] to make it feasible for interconnection applications in HMGs. In this modified UIPC, the number of series transformers and power converters has been reduced compared to conventional UIPC. Moreover, a DC-link of UIPC can be connected to DC sub-grid; however, due to fluctuations in the output power and voltage of the DC sub-grid, a stiff observer based sliding mode controller has been used to regulate DC voltage and control the power exchange between the AC and DC sub-grids. Moreover, another power converter named as Line Power Converter (LPC) is also connected in series with the transmission line, which is responsible for the injection of controllable series voltage. A generalized schematic of UIPC is presented in Fig. 17. The same structure has been adopted by the authors in [78] to interconnect numerous sub-grids in HMG system. This topology provides flexible power flow between AC and DC sub-grids.

TABLE 4. **Description of interconnecting methods in HMG.**

Method	Description
Single-stage ILCs	Single stage ILCs with different topologies have been used for interconnection of AC and DC sub-grids in HMG. The reliability of these ILCs is low and the power transfer capability is also limited
Two-stage ILCs	ILCs are connected in parallel or series to increase the reliability and transferred power. Moreover, different control strategies have been used that improve the operational performance.
Energy Router	ER is able to interconnect several AC and DC sub-grids as it consists of different DC/AC and DC/DC power converters.
SST	It is used to interconnect HMG by providing more degree of freedom in power controllability and transferring.
FACTS	UIPC, UPQC, and UPFC are the effective tools that provide flexibility in power flow and HMG system interconnection.

The authors in [79] proposed an HMG system in which UPFC is used for interconnection purposes, as shown in Fig. 18. UPFC consists of a parallel and series power converter along with a common DC-link. This DC-link is supported by DC-DC power converter that integrates different loads and DGs and facilitates power decupling and voltage regulation at the DC-link. Moreover, in this work, a modular structure is also presented that enables an HMG to integrate more DVs and local MGs. The control of the converters is established in $\alpha\beta$-reference frame and close-loop system is analyzed to ensure the system's stability in case of integration of different variable DGs.

A brief description of these interconnecting methods is presented in Table 4.

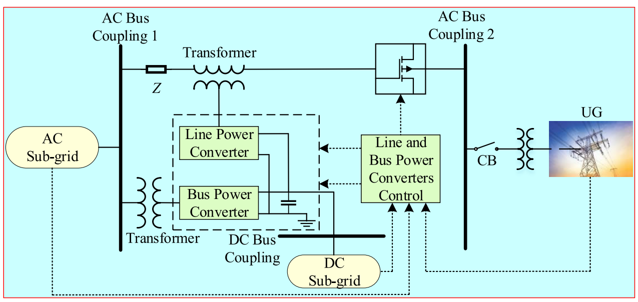

FIGURE 17. **Schematic of HMG interconnected by UIPC.**

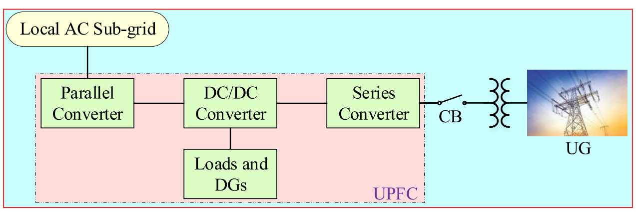

FIGURE 18. **Schematic of HMG interconnected by UPFC.**

C. ASSESMENT OF INTERCONNECTION METHODS

The interconnecting methods discussed above offers numerous advantages but at the same time there are numerous challenges that are association with it. For instance, the main advantageous features of single stage ILCs are (a) simple control, (b) low cost, (c) can be equipped with ESS that make the DC side more reliable, (d) some advanced structures such as Γ-Z-Source BILC and quasi-Z-Source have high reliability and efficiency compared with the conventional BILC. However, beside these advantageous features, the main challenges of single stage ILCs are (a) low reliability, (b) the AC and DC sub-grids in an HMG system have different dynamic characteristics, i.e., an AC sub-grid may operate at different voltage, phase, and frequency levels while a DC sub-grid may operate at different voltage levels; therefore, the system is non-linear and time varying [80], (c) DC based generating units such as PV have intermittent power generation as a result the DC-link voltage may fluctuate which causes oscillations in the exchanged power [77], (d) as an HMG consists of both unstructured and parametric uncertainties due to stochastic nature of DGs and loads, therefore, it is very crucial for the single stage ILCs to show efficient performance and ensure flexible power exchange capabilities [81], (e) the power transfer capability is limited, (f) the duty cycle of ILC may contain uncertain parts which results in fluctuation in output voltage [82], and (g) the size of the filter is directly linked with the electrostatic and electromagnetic energies stored in capacitance and inductance of LC filter respectively, therefore, the size should be optimized as much as possible [83].

Similarly, the advantages that two-stage ILCs offer includes (a) can transfer large amount of power between AC and DC sub-grids, (b) modular base structure, (c) high reliability, and (d) have greater degree of freedom in terms of control. However, the main challenges which are associated with these ILCs are (a) if the converters are connected in parallel then its operation is challenging as the output voltage of every ILC must be equal so that they are able to eliminate the circulating current, reduce the power losses, and ensure stable power sharing between AC and DC sub-grids [84], (b) power must be shared according to the rating of ILC, i.e., higher the rating of ILC the larger the share of power transfer and vice versa [85], (c) high cost compared to single-stage ILCs, (d) during the occurrence of fault, the fault current is unequally distributed among the ILCs that may result in excessive flow of current from their rated capacity in a particular ILC which may lead to disconnection of the ILC [86], (e) a change in line inductance or resistance causes a change in the power transferring capability of the ILC which may results in high circulating current and high power losses [87], (f) in a cascaded or parallel ILCs the harmonics may causes a phase deviation at the output voltage, as a result, the stability of the system may be affected [88], (g) similar to single-stage ILCs, two-stage ILCs must be able to perform different control tasks which make their control complex [89], and (h) in a two-stage ILCs, the DC-link voltage is more prone to instability compared to single-stage ILCs, therefore, the controller must be more elaborated to cope with this challenge [90].

The ERs are more economical for an HMG system which consists of more DC based generating units that AC as it avoids the conversion process in case of DC sources [91]. Moreover, a multiport converter can be utilized in the ER structure that makes it control structure simple and cost effective particularly in some cases compared to parallel-connected ILCs [70]. Besides these advantages, there are some challenges that are associated with ERs, such as: (a) ERs carry high input voltages and output currents, therefore their design is more complex, (b) in most scenarios the ERs are less reliable, expensive and less efficient than the ILCs [16], (c) due to usage of a single UG side DC/AC converter, the reliability of the ER is highly affected. In this scenario, if this converter fails, then the HMG is disconnected from the UG; as a result, the stability of the system may be affected [69], (d) the reliability of ER is affected by using high number of power converters, and (e) due to integration of numerous power converters at the DC bus, the stability of DC-link voltage is difficult.

The main advantageous features that SST offer includes (a) it provides bidirectional power exchange among sub-grids and HMG with UG without the problems which are related to two-stage ILCs, (b) it is less challenging compared to two-stage ILCs for interconnection purpose, and (c) it presents more flexibility for distribution system in terms of reactive power compensation, power factor correction, harmonics filtering, protection, voltage control, etc. However, these prominent advantageous features there are some challenges which are associated with this technology such as (a) a medium frequency DC-DC converter in needed for SST to provide galvanic isolation for the system, (b) it is difficult to completely eliminate the voltage oscillations at the DC-link, (c) a unified coordinated controller is very difficult to design for a system that consists of DC-DC, AC-DC, DC-AC, and SST.

The main advantageous features that small-scale FACTS offers in HMG application includes (a) large amount can be transfer between AC and DC sub-grids, (b) shows high reliability, (c) can provide voltage regulation at DC-link, (d) it enables DC sub-grid in HMG is able to accommodate more loads and DGs with regulated output, and (e) ensure efficient bidirectional power flow among AC and DC sub-grids. However, beside these numerous advantages there are still numerous challenges that are associated with small-scale FACTS such as (a) the cost of the transformers become high when conventional UIPC and UPFC are used, (b) the controllability of series and parallel connected converter of UPQC is a very challenging task when they are connected to the DC-link of the DC sub-grid.

The benefits and challenges related to every interconnection technique described in detailed above and are summarized in Table 5. Keeping the benefits, features, and challenges of every technology appropriate interconnection method should be selected according the requirement of application. Moreover, during the review process following research gaps are identified (a) the interconnecting methods should be investigating by considering stochastic generation, critical loads, and amount of available energy storage in respective sub-grids, (b) the ILCs should be designed that consists of minimum component count especially the semiconductor switches, (c) besides these interconnecting methods other methods should be investigated that effectively interface different sub-grids, (d) control strategies should be develop that enhances the robustness and flexibility of the system, and (e) the design of the ILCs needed to be modified in such a manner that they provide virtual inertia to the system in the absence of synchronous DGs or the inverter dominated HMG.

IV. HMG CONTROL

In HMGs, both AC and DC MGs are usually interconnected through ILCs to provide an optimal configuration [92]. However, due to presence of different DGs, power converters, ESSs, and loads, it is very difficult to operate and control an HMG. Therefore, the controller must have the ability to overcome these control challenges: (a) in an AC sub-grid, the non-linear loads cause harmonics that result in phase deviation and voltage fluctuation; therefore, this must be considered during the design process [93], (b) the design of the converter and controller should be such that it ensures DC-link stability. As HMG may have some DGs (such as PV system) that have variable output, which may result in voltage fluctuation at the DC-link. This fluctuation may cause oscillations in the exchanged power that may lead to system instability. In an AC sub-grid, this problem may occur, but a major concern is with the DC side [77], (c) the duty cycle of ILC may contain some uncertain part that causes a variation in output voltage waveforms; therefore, this challenge should be addressed [94], (d) due to the absence of global variables, it is difficult to regulate the voltage and frequency and ensure power-sharing [95], (e) a controller should realize a smooth transition from IS mode to GC mode as well as from GC mode to IS mode [96], (f) in GF mode, the ILC generally acts in power control mode; therefore, the controller must have the capability to ensure an accurate power exchange between the AC and DC sub-grids and to/from the UG. Moreover, in this operating mode, ILC is responsible for regulating the DC bus voltage in DC sub-grid and the frequency and voltage in AC sub-grid [97], (g) to avoid the electrical balance on an individual source and optimize the operation of ESS, an advanced energy management system should be employed that maintains a power balance among all the sources and ESSs [98], and (h) a droop controller should be independent from the line impedances between the AC/DC buses and the inverter to ensure accurate load sharing among all the energy generating resources [99].

To fulfil these control objectives, the control of HMG is generally implemented using three architectures, namely, centralized, decentralized, and distributed control architectures, as discussed in Section II. A comparative analysis of these three control architectures is presented in Table. 6.

TABLE 5. Assessment of interconnecting methods in HMG.

Method	Benefits	Challenges
Single-stage ILCs	• Simple control • Low cost • Usage of ESS makes the DC side more reliable • Advanced topologies, i.e., Γ-Z-Source and quasi-Z-Source are more reliable and efficient compared with conventional ILC	• Low reliability • Due to different dynamic characteristics of system, it is non-linear and time varying • DC-link voltage fluctuation causes oscillations in the exchanged power • Stochastic nature of DGs and loads make it difficult to ensure accurate power exchange • Limited power transfer capability • Uncertain parts in ILC's duty cycle may results in output voltage fluctuation • Optimized size of the LC filter should be selected
Two-stage ILCs	• Able to transfer large amount of power between AC and DC sub-grids compared to single-stage ILCs • Modular base structure • High reliability • High degree of freedom in terms of control	• Difficult to maintain same output voltage in case of parallel connected ILCs • Difficult to ensure power sharing according to the rating of ILCs • High cost compared to single-stage ILCs • Fault current problems • Phase difference in output waveforms can cause system instability • DC-link voltage is more prone to instability compared to single-stage ILCs
ER	• ERs are more economical for HMG systems which consists for more DC based DGs that AC • Multiport converter can be utilized in the ER structure that makes it control structure simple and cost effective	• ERs carry high input voltages and output currents; therefore, their design is more complex than ILCs • Complex control structure • The usage of a single UG side DC/AC converter make ERs less reliable • Reliability of ER is affected by using high number of power converters • Stability of DC-link voltage is difficult to achieve
SST	• Bidirectional power exchange among sub-grids and HMG with UG is achieved by neglecting the problems related to two-stage ILCs • More flexible for distribution system in terms of reactive power compensation, power factor correction, harmonics filtering, voltage control, etc.	• Medium frequency DC-DC converter in needed for galvanic isolation • Difficult to eliminate voltage oscillations at DC-link • Coordinated controller is difficult to design for system which consists of DC-DC, AC-DC, DC-AC, and SST.
Small-scale FACTS	• Large amount can be transfer between AC and DC sub-grids • High reliability • DC-link voltage regulation • Can accommodate more loads and DGs with regulated output at DC side • Bidirectional power flow among AC and DC sub-grids	• High transformers cost when conventional UIPC and UPFC are used • Controllability of series and parallel connected converter of UPQC is a very challenging task when they are connected to the DC-link of the DC sub-grid.

These control architectures use a hierarchical control structure to accomplish the control objectives. Hence, in the next subsequent section, initially, a detailed literature review of

TABLE 6. Comparison of different control architectures.

Architectures	Merits	Demerits
Centralized	Easy implementation Optimal decision Good power quality Accurate power-sharing Less circulating current among ILCs	Difficulty in scalability Slow response speed Less reliable and flexible Expensive and complex Depend on communication network High computational burden
Decentralized	Less expensive Scalability Flexible and modular Less computational burden Not require communication network Fast response speed	Poor power quality Not precise power management More circulating current among ILCs Deviation in frequency and voltage control Does not guarantee an optimal decision
Distributed	Fast response speed Accurate power-sharing Less circulating current among ILCs Accurate frequency and voltage regulation High power quality High reliability	Data transmission delays Less secure during information sharing Difficulty in expendability Less flexibility and redundancy

hierarchical control structure is presented. Moreover, different control strategies applied to the ILCs are discussed. Finally, different control schemes that are used in different operating modes including the mode transitions to attain the power management in HMG are explained.

A. HIERARCHICAL CONTROL STRUCTURE

In a hierarchical control structure, the control functions are distinguished into primary, secondary, and tertiary control

levels depending on the timeframe during which control tasks are needed to be performed. A generalized schematic of the hierarchy is presented in Fig. 19, and the objectives of every control level are discussed below.

1) PRIMARY CONTROL

It is the first level of the hierarchy, has the fastest response time compared to other control levels, and sends the control signals at intervals of milliseconds to the inverter to perform its mandatory control actions. It is responsible for regulating the frequency and voltage while ensuring appropriate power sharing and management [100]. For primary control, existing literature recommends two converter control modes, i.e., Grid Forming Mode (GFM) and Grid Following Mode (GFWM).

Based on the operating mode of HMG, the inverter control strategy should be selected (GFM or GFWM). A GFWM is considered as Current Controlled Voltage Source Inverter (CCVSI) having parallel shunt impedance. In GFWM, the UG is responsible for maintaining a stable frequency and voltage at the HMG. The DGs are also operating in CCVSI for maximum power generation. Similarly, the ESS units are operating in charging mode and adjust the frequency and voltage when they deviate from their permissible bandwidth limits. A GFM can be visualized as an ideal Voltage Controlled Voltage Source Inverter (VCVSI) having low output impedance; therefore, an exact synchronization system is required by the voltage source to work synchronously with other GFMs. Hence, GFMs are more feasible in scenarios where an HMG is operating in IS mode. In GFM, the DGs and ESS units are responsible for regulating the frequency and voltage of both AC and DC bus bars according to their set points. Hence, all the DGs are operating in VCVSI and ESS units are operating in discharging mode. Based on the number of DGs participate in voltage control, GFM can be further divided into two categories, i.e., (a) only one DG operates in GFM and is responsible for ensuring a regulated frequency and voltage while other DGs operate in CCVSI [101] and (b) more than one DG operates in GFM to regulate the frequency and voltage; therefore, proper synchronization is needed for the DGs that are operating in GFM [102].

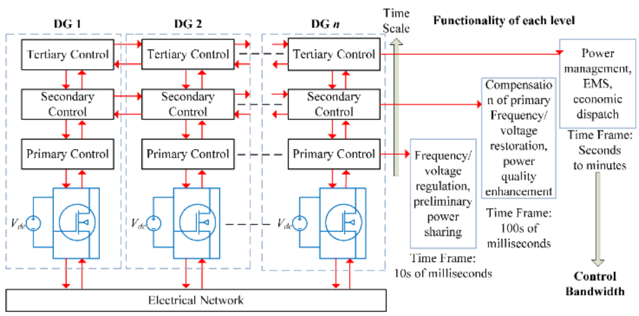

FIGURE 19. **Schematic of hierarchical control structure.**

A droop controller is usually used at the primary control level to accomplish the control objectives such as the authors in [103] proposed a Current-Voltage (I-V) based droop controller for appropriate sharing of power between parallel ILCs in an HMG. Proportional Resonant (PR) and PI controllers are used to regulate the output current and voltage of the ILCs. Moreover, (I-V) droop controller is presented as $V_{DC} = V_{DC-ref} - (R_{vd} i_{DC})$; where, V_{DC}, V_{DC-ref}, and i_{DC} are the actual voltage, nominal voltage, and current of the DC bus respectively, while and R_{vd} represents a virtual resistance. This droop controller did not realize the AC side droop controller. Hence, the authors in [104] proposed an AC (P-f) droop on the AC side and DC (P-V) droop on the DC side to overcome the limitations of the work presented in [91]. These two droops are linked together and their coordination is used in ILC control to ensure a proportionate power-sharing of both AC and DC sub-grids. Similarly, the authors in [105] proposed a bidirectional droop control strategy for an HMG having a primary focus on power control of the ILC during different operating modes. In this method, PMS generates the power references for the ILC by measuring the frequency and voltage from AC and DC sub-grids, respectively, along with the droop characteristics. This methodology enables an HMG to share the load among all the existing power sources.

2) SECONDARY CONTROL

Although accurate power sharing is achieved by the primary controller but it pushes the voltages and frequencies away from their nominal values. Therefore, to overcome these limitations, a secondary control level is designed having the key objectives is to eliminate the DC bus voltage deviation in the DC sub-grid and the AC voltage and frequency deviations in the AC sub-grid of an HMG system. Moreover, harmonics compensation, voltage unbalancing, power quality enhancement, and reconnection of MG with UG, etc. are few of the control objectives performed by the SC level [106]. A secondary controller is designed to operate at a slower time-frame compared to the primary control level to facilitate the steady-state-attainment of primary controller before SC updates its points. SC level works primarily in cooperation with the communication network and is well suited for optimization problems such as economic dispatch and power-sharing optimization along with restoration and synchronization problems [31]. Based on the communication network, the SC can be categorized as centralized, decentralized, and distributed control.

In a centralized secondary control approach, a global central controller of an HMG performs the power management. A global central controller initially collects the data from ESS units, critical loads, and DGs, then measures it and makes the mandatory calculations. Based on the calculations, the controller send sends the signals to perform the required tasks. Different centralized secondary controllers have been used in HMG to perform different tasks. For example, the authors in [107] proposed an optimization based supervisory controller with a main objective is to maximize the utilization of energy generated by RESs in an HMG system. Moreover, some other control objectives are also achieved in this work, such as minimizing the use of diesel generators, limiting the usage of ILCs, and increasing the battery's life. In this work, the intermittency of RESs and generation prediction error are considered along with the battery charging and discharging statistics which are supervised by the controller to ensure accurate power management. A centralized architecture based coordinated controller for HMG systems operating in IS mode as well as in GC mode is presented in [83]. In GC mode, a PMS ensures that the PV and wind energy systems are operate at MPP. However, in IS mode, based on the PMS, the PV and wind energy system are considered to be operate either in MPPT condition or off-MPPT condition. The authors in [108] proposed an intelligent supervisory based centralized control strategy for an HMG system. In this work, BSS and PV system are considered in DC sub-grid side while diesel generator, BESS, and wind energy system are considered in AC sub-grid side. A Fuzzy Logic (FL) based control scheme is employed for the charging and discharging of BESS in AC and DC sub-grids in order to achieve different operating modes. A total of 15 operating modes are considered in this work, which include 4 modes where no power exchange occurs between the sub-grids, while in the remaining 11 operating mode the power exchange occurs between the AC and DC sub-grids. The authors in [109] proposed an EMS for BESS based HMG. An EMS consists of optimization problem having a primarily objective is to minimize the operating cost of the system by considering a dual stage charging phenomena for BSS. Moreover, a FL based supervisory controller is also employed that efficiently responds to a minuet variation of UG power by changing the set points of the DGs accordingly.

Different from a centralized controller, a decentralized controller is implemented at the local level. Therefore, ESS units and DGs are responsible for performing the control actions (voltage and frequency regulation, power management, etc.) [110]. As no global controller is involved in this approach, therefore, in case of any fault only the faulty part is disconnected from the HMG system while remaining part perform its operation. A decentralized coordinated control strategy based on event triggered mechanism for HMG is presented in [111]. A two-level control strategy is used in this work in which an EMS is designed in the upper control level to maximize the environmental and economic benefits, whereas, a in the lower control level that control the system dynamics. The authors in [112] proposed a decentralized PMS and load sharing method for HMG system that comprises of PV and ESS unit. In this work, the operation of HMG is divided into five states (battery charge limit, battery disconnect, battery charge–discharge, output power limit, and PV power curtailment) and based on the operating states a modified droop controller is utilized.

A distributed secondary control approach in an HMG system allows communication between multiple energy generating sources and the local controllers to regulate its voltage and frequency while ensuring accurate power sharing and management. In [113], the authors proposed a multi framework distributed consensus based economic dispatch controller. The main objectives of this research work are to ensure the protection, economic operation, and stability the system in case of different system and external uncertainties. An average consensus based two layered distributed cooperative frequency controller for AC coupled HMG is proposed in [114]. The agents involved in this work are associated with ESS unit, DG, and loads. Moreover, a multistage load shedding phenomena is also implemented such that a controller regulates the frequency of the system even in scenario when there is a deficiency of primary reserve. A distributed secondary controller based on model predictive controller is proposed in [115] which control some variables with predefined bands and some variables to specific values in the HMG system. Specifically, the frequency and voltage are restored within its limit bands while optimal dispatch of P and Q is achieved. In [116], the authors proposed a consensus based distributed controller for voltage regulation in DC sub-grid and voltage and frequency restoration in AC sub-grid while attaining optimal dispatch in IS HMG. The controllers in this work mainly depend on the local measurements and information from neighbouring devices therefore an HMG acts as a single electrical entity not as three independent systems (AC, DC, and ILC) which interact with each other. A multi agent based distributed secondary controller of HMG operating in IS as well as in GC mode is proposed in [117]. The HMG consists of PV, diesel, fuel cell, biodiesel, and natural gas as energy generating sources. The frequency and voltage restoration is carried out by controlling the generating units like diesel, fuel cell, biodiesel, and natural gas while PV system acts as a supplementary source. This multi-agent system supports parallel computation and increase the robustness of the HMG system.

3) TERTIARY CONTROL

It is the highest control level in the hierarchical structure and has the lowest response time speed among all the control levels. The main functionalities of a tertiary controller include (a) optimizing the HMG operation based on weather forecasts, energy costs, etc., (b) controlling P and Q of DGs, sub-grids, and ILCs based on economic, parametric, and technical criteria, and (c) connecting of HMG with UG [14]. This control level can be implemented in a centralized as well as in a distributed control architecture.

In a centralized control, P and Q are evaluated at the point of common coupling, whereas the reference values of P and Q are calculated based on MG power demands and operations of energy market. Hence, this way the efficiency, power quality, and cost-effective operation of the system is ensured. The authors in [118] proposed a centralized architecture based tertiary control (EMS) for HMG system operating in IS mode. In this work, a main consideration is given to an optimal energy dispatch with intentions to maximize the economic benefits coming from ESS units, RESs, and UG. Moreover, the energy demand and generation profiles, and forecast of electricity price are considered to optimize the operation of the whole system. Similarly, the authors in [119] proposed an optimal tertiary control for HMG system which is based on mixed integer linear programming method. This method ensures optimal power flow between the AC and DC sub-grids and between the HMG and UG.

A tertiary control level in distributed architecture has been implemented by numerous researchers, such as the authors in [120] proposed a master-slave approach based control scheme. In this method, just like the primary and secondary control levels that uses the master to ensure the secure, reliable, and stable operation of HMG while the slaves follow the commands of the master to inject the available power into the system. Similarly, the authors in [121] proposed a consensus/gossip based distributed tertiary control strategy for HMG. In this approach, gossip algorithm is used to acquire the global information while the optimization algorithm is utilized to obtain the local optimum decision which results in improved power quality. Moreover, to improve the quality of power, a tertiary controller also generates the compensation signals for the local controllers of the DGs. Furthermore, a tertiary control approach requires two communication links;

one link is allocated to consensus/gossip based controller, while a second link is allocated to the primary controller.

B. CONTROL OF ILC

The main functionality of ILCs includes voltage regulation at the DC bus, plug-and-play operation, frequency and voltage regulation at the AC bus, and bidirectional power flow between sub-grids [121]. When an HMG is connected with the UG, then the voltage at the DC bus is regulated by the ILC by providing active power, while the P and Q in the AC sub-grid are maintained by the UG. On the contrary, when an HMG is operating in IS mode, coordinated control among DGs, ILCs, and ESS units is required to regulate the frequency and voltage of AC sub-grid and the DC bus voltage of DC sub-grid [122].

ILC enables an HMG to exchange excess or required power on both AC and DC sub-grids. It should be remembered that the power-sharing capacity that is transmitted between AC and DC sub-grids depends on the capacity of ILC. Moreover, ILC cannot be considered as a main controller as they did not dissipate or provide power from load or source, but instead it only provides the primary regulation, i.e. its functionality is only limited to switch power among the sub-grids. Moreover, in scenario, when one of the sub-grids has excess power generation and an adjacent connected system has high power requirements, in such cases, ILC helps in appropriate PM and transfer the power from one sub-grid to another sub-grid. Furthermore, when ILC perform the deviation compensation in a scenario when two sub-grids have an excess power generation or demand then only one sub-grid will get benefited and stabilize its performance while the other sub-grid suffers from high deviation [123]. Due to these limitations different control strategies are developed for ILC. Some of the important ILC control approaches are discussed below in detail.

1) DROOP BASED METHODS

The authors in [66] proposed a droop controller for HMG system, which contains an ESS unit with an ILC. A BSS or capacitor at the DC-link of the ILC can be used to store energy. Moreover, a control strategy ensures the regulation of a DC-link while considering the effects of DC-link capacitor. Similarly, an improved droop strategy for ILC based HMG is presented in [124]. The controller is capable of attaining the appropriate power-sharing between the DC and AC sub-grids in IS as well as in GC mode. In IS mode, the performance of an HMG is improved by the controller by ensuring accurate power distribution between the two sub-grids. In GC mode, a controller ensures the efficient performance of the DGs in a DC sub-grid and also stabilizes the DC-link voltage. A hierarchical control structure based on the droop controller for HMG is proposed in [125]. Due to its hierarchical structure, the control is able to perform multiple functions and has the ability to simultaneously ensure accurate PM and voltage support.

In [126], a droop controller based multi-objective control strategy for HMG is presented, which consists of numerous AC and DC sub-grids. In this system, every ILC is equipped with a local droop controller which communicates with a centralized controller to perform the control actions. A coordinated control strategy based on a droop method for ILC is presented in [127]. This method enhances the operational reliability of the system and ensures appropriate power-sharing among the interconnected sub-grids. The authors in [128] proposed a dual loop droop based controller for parallel connected ILCs. This work uses a hierarchy concept that is implemented in a synchronous reference frame with a main objective is to remove the circulating current among the ILCs and improve the reliability and power quality of HMG. Similarly, another dual loop droop based controller for an HMG that consists of numerous AC and DC sub-grids is presented in [129]. In this work, all the ESS units, and AC and DC sub-grids that have different frequencies and voltages are assumed to be lumped unit to enhance the PM and simplify the design of the controller.

The authors in [130] proposed an improved droop controller for parallel connected ILCs. In this method, initially, the current and power error have been calculated, and then the controller acts to remove the current and power mismatch between the measured and reference values. In [131], f-P and E-Q droop control strategy based on distributed architecture for ILC based HMG is presented. A data driven based improved droop controller for ILCs has been proposed in [132]. A dual loop based model free adaptive droop controller for ILCs has been presented in [133]. In this work, initially, the power consumption of every sub-grid and the direction of power transferred is measured. Due to the usage of two droops, efficient voltage regulation at DC sub-grid and voltage and frequency regulation at AC sub-grid have been attained.

2) INSTANTANEOUS POWER THEORY BASED METHODS

The authors in [134] studied the operation of parallel ILC in an HMG system under unbalanced grid voltages. In these works, an instantaneous power theory is used to split the power oscillation terms in formulating P and Q flow. Hence, a controller for ILCs has been proposed to remove these oscillation terms and provide accurate power sharing among AC and DC sub-grids of HMG system. This can be accomplished by choosing one ILC as redundant ILC (i.e., an ILC with higher ratings), which is responsible for carrying the overcurrent that appears during faults. Hence, this methodology allows the other ILCs to operate with their nominal currents. Although this control strategy improves the quality of active power but it lacks the ability to remove reactive power oscillations.

3) UNIFIED CONTROL OF ILC

A unified control of ILC presented in [135] consists of two control loops, i.e., an inner frequency/voltage control loop and an outer power control loop. The ESS units and DGs on both DC and AC sub-grids are classified into two categories, i.e., slack terminals and power terminals. The power terminals are ESS units and DGs on both DC and AC sub-grids that work in MPPT mode, while the slack terminals are ESS units and DGs on both DC and AC sub-grids, which are used to regulate the frequency and voltage. Let consider that the P_{AC} and P_{DC} are the real output power of AC and DC sub-grids respectively and the slack droop characteristics take the following form as:

$$E_{DC} = E^*_{DC} + \left(P^*_{DC} - P_{DC}\right)/\mathbf{K}_{DC}$$
$$\omega_{AC} = \omega^*_{AC} + \left(P^*_{AC} - P_{AC}\right)/\mathbf{K}_{AC} \quad (1)$$

where, E_{DC} and E^*_{DC} are the slack bus and DC bus terminal and reference voltage respectively, P^*_{DC} is the reference real power of the DC bus, and $\mathbf{K}_{DC}$ is the DC bus droop gain. Similarly, ω_{AC} and ω^*_{AC} are the slack bus and AC bus terminal and reference frequency respectively, P^*_{AC} is the reference real power of the AC bus, and $\mathbf{K}_{AC}$ is the AC bus droop gain. In normal condition, the real active power output of PCC of both sub-grids is maintained based on the potential ($\mathbf{K}$). Thus, the power error (ΔP) at PCC of both sub-grids can be given as:

$$\Delta P = P_{AC} - P_{DC}\mathbf{K} \quad (2)$$

Put (1) in (2) and solve it would give us:

$$\Delta P = \left[P^*_{AC} + \mathbf{K}_{AC}\left(\omega^*_{AC} - \omega_{AC}\right)\right] - \mathbf{K}\left[P^*_{DC} + \mathbf{K}_{DC}\left(E^*_{DC} - E_{DC}\right)\right] \quad (3)$$

The output power can be calculated by using (3) and the reference set point value of real power can be calculated by using the transfer function of the regulator $G(s)$. Moreover, the phase angle (δ) and voltage amplitude (E) references for the inner control loop are calculated using P-f and Q-E droops respectively [136]. Furthermore, a PR controller is used to improve the dynamic performance and reduce the steady-state error in the AC voltage.

4) INTELLIGENT CONTROL METHODS

Different intelligent control techniques, such as Artificial Neural Network (ANN), FL, etc., have been used to control the ILC of the HMG system. For instance, the authors in [120] proposed a FL based supervisory control for HMG that consists of AC and DC sub-grids which are interconnected through ILCs. The proposed supervisory control manages the transfer of power among the sub-grids and is capable of extracting the maximum power from RESs based generating units. A FL based control scheme usually follows rules, according to which the operating modes of ILCs are configured. For example, the current at the DC bus (I_{DC}) of DC sub-grid can be assumed as a parameter that affects the switching characteristics of ILCs, then we may have such rules in the interface system:

$$\begin{cases} \text{if } \Delta P_{DC} \text{ is } PB \text{ and } \Delta\text{SOC is } NB, & \text{then } I_{DC} \text{ is } PB \\ \text{if } \Delta P_{DC} \text{ is } PB \text{ and } \Delta\text{SOC is } NS, & \text{then } I_{DC} \text{ is } PB \\ \text{if } \Delta P_{DC} \text{ is } PB \text{ and } \Delta\text{SOC is } ZO, & \text{then } I_{DC} \text{ is } ZO \end{cases} \quad (4)$$

where, ΔP_{DC} presents a change in the active power at DC bus;ΔSoC denotes a change in the SOC of battery integrated with the DC-link of ILC; and PB, NB, NS, and ZO are the membership functions that denotes Positive Big, Negative Big, Negative Small, and Zero respectively.

In [137], the authors proposed an ANN based control scheme for the control of ILC in HMG system. The main objective of the controller design is to reduce the fuel cost, maximize the utilization of energy generating resources, improve the power quality, and generation of optimal switching pattern for the ILCs. The authors in [138] proposed a hybrid technique in which an adaptive ANN is combined with fuzzy logic for the control of ILCs and management of various energy generating sources such as wind turbines, PVs, and fuel cells. Moreover, this approach extracts the maximum power from RESs and minimizes the energy cost. In [139], the authors have presented a genetic algorithm based adaptive ANN controller to regulate the voltage and power generation in PV-wind HMG. This controller extracts the maximum power from the PV and wind systems through MPPT techniques and increases the power handling potential of the whole system.

5) ROBUST CONTROL METHODS

The authors in [140] proposed a robust controller based on Linear Matrix Inequality (LMI) for ILC. In this work, the demand-generation graph is balanced by ensuring accurate power transfer between the sub-grids and the UG. In [141], a robust back-stepping controller was used to control the ILC in HMG. The stability of the close loop system is validated through Lyapunov theorem. A robust controller based on predictive method for ILCs has been proposed in [142]. In this work, the power quality issues in both AC and DC sub-grids of HMG have been addressed while establishing stable power transfer among sub-grids. A double integral Sliding Mode Controller (SMC) for GC connected HMG is presented in [143]. In this work, an independent MPPT has been used to extract the maximum power from the RESs while the proposed controller has been utilized to regulate the DC bus voltage. Moreover, the stability of the system under different uncertainties and challenging conditions is ensured through Lyapunov candidate.

A centralized architecture based on fast integral terminal SMC for HMG is presented in [144]. This controller regulates the voltage at the DC bus and frequency and voltage at the AC bus during IS as well as in GC mode. Moreover, the stability of the controller is ensured through Lyapunov stability criteria. In [145], a robust SMC strategy based on observer control concept for ILC is presented. In this work, the non-linear dynamic model of ILC is presented as two decoupled linearized sub-models that can be controlled easily. The linearization of ILC model is achieved by using Akerman pole placement method and Lie's derivative theorem. In [146], the authors use the same previous concept and make the observer adaptive by the variable design parameter. Moreover, in this work, a flatness concept has been used to present the flat model of ILC dynamics.

6) PREDICTIVE CONTROL METHODS

In [147], an MPC scheme is presented to regulate the frequency and voltage in AC/DC HMG. However, this work lacks discussion of the power-sharing mechanism among the sub-grids or HMG with the UG. Similarly, the authors in [148] proposed an MPC for bidirectional ILC in HMG. This controller accurately regulates the voltage and frequency at sub-grids but the power balancing between bidirectional ILC and AC sub-grid is not taken into consideration. The authors in [149] proposed a Model Predictive Controller (MPC) for the ILCs used in the PV-wind HMG system to regulate the voltage at AC and DC sub-grids and frequency at AC sub-grid. Moreover, this controller ensures accurate power-sharing among the sub-grids. The authors in [150] presented an MPC to provide an optimal regulated current for the ILC. Moreover, this controller also provides protection to ILCs against faults and provides an optimal power transfer between the AC and DC sub-grids. In [151], the authors presented a distributed architecture based MPC for the ILCs of HMG. This strategy is based on the hierarchical structure having a main functionality is to resolve the load sharing and power quality issues in IS HMG.

The main advantages and challenges/disadvantages of different ILCs control techniques are summarized in Table 7.

C. POWER MANAGEMENT

Numerous energy generating sources and ESS units are connected to the AC and DC buses of the HMG systems, while these buses are interconnected with each other through bidirectional ILCs. The output power of these DGs and ESS units is determined by the Power Management System (PMS) based on the operational characteristics of HMG. A generalized schematic of PMS in HMG network is presented in Fig. 20. From Fig. 20, it can be seen that it consists of a centralized PMS unit to which data from all the components of the HMG is fed in order to determine efficient power flow between the energy resources. After applying the PM algorithm the output commands are sent to the local controllers of the ILC, AC sub-gird, and DC sub-grids to enable them to accurately track the set-points. Hence, PMS is responsible for the stable performance of HMG and also regulates the voltage and frequency on both sub-grids. Therefore, in this section, a detailed review of different control schemes in different operating modes is presented.

TABLE 7. Features of ILCs control techniques.

Control Method	Advantages	Challenges
Droop Based Method	• Fast transient response • Reliable operation • Easy implementation • Communication free (in decentralized and distributed control architecture) • No zero sequence current among ILCs	• Deviation in frequency and voltage may lead to system instability • In some HMG cases, the gains are needed to be adaptive • Sub-optimal in different cases
Instantaneous Power Theory Based Method	• Very low active power oscillation • Efficient operation of HMG under unbalanced faults	• Required redundant ILC • The failure of redundant ILC leads a system to less reliable • High reactive power oscillations
Unified Control	• The inner voltage and frequency and outer power control loops ensure smooth mode transition • Simple implementation • Can be implemented without communication network	• Required robust structure • Accurate power flow can be attained by trial and error method
Intelligent Control	• Easy algorithm implementation • Fast dynamic speed • High flexibility during designing • High reliable • Accurate power sharing	• Need training data (e.g. ANN controller) • Optimal selection of membership function is difficult
Robust Control	• Fault tolerant • Switching control structure (e.g. in case of SMC) • Shows high robustness against parameter variations	• Over conservative (such as H∞ controller) • Sub-optimal in various cases
Predictive Control Methods	• Provide efficient performance in case of uncertainties or disturbances • Fast dynamic response • Reduced off-set error	• High computational requirement • Require accurate system model • Difficult implementation

1) GRID CONNECTED MODE

In GC mode, power balancing can be attained either in un-dispatched or dispatched output power mode [152]. In an un-dispatched power mode, all the DGs in both DC and AC sub-grids operate in a current controlled mode (the frequency and voltage are determined by UG, while the reference power is tracked by regulating the output current of DGs). It means that an HMG is injecting power into UG while ESS units are in charging state; moreover, in this mode, the voltage at the DC-link of DC sub-grid is regulated by the ILC [153]. In dispatched mode, all the DGs and ESS units operate either in

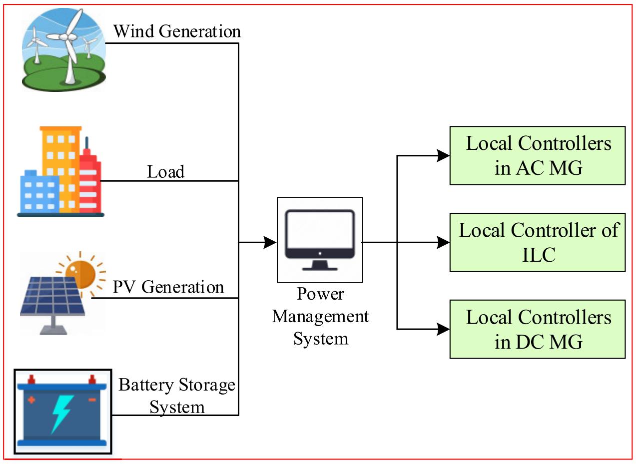

FIGURE 20. Generalized schematic of PMS.

CCM or in VCM. In VCM, the DGs operate as synchronous generators, and their output powers can be controlled by regulating their output voltages [154]. A bidirectional ILC can be operated in power control modes, DC sub-grid voltage control, and AC sub-grid voltage control based on the coordination between DGs, ESS units, AC sub-grid, DC sub-grid, and ILC. Moreover, in this mode, the dispatched power and DC sub-grid voltage can be regulated by using two methods. In a first method, the ESS units and DGs in AC and DC sub-grids are coordinated with each other to regulate the dispatched power, while the voltage in the DC sub-grid is regulated by the ILC. In a second method, the DGs, ESS units, and ILC in the AC sub-grid are responsible for delivering the required dispatched output power, while the ESSs units and DGs in the DC sub-grid are responsible for regulating the DC-link voltage [155].

2) ISLANDED MODE

In IS mode, to regulate the frequency and voltage in AC sub-grid and voltage in DC sub-grid and to balance the power generation and load demand, a coordinated control among all DGs, ESS units, and ILCs is very essential. In IS mode, master slave [156], droop method [157], etc. are used for the PM in AC sub-grid, while in DC sub-grid, indirect power balancing method [158], etc. can be used to attain voltage management. Moreover, in autonomous mode, DGs and ESS units connected to AC and DC sub-grids are used for AC and DC bus voltage regulation, respectively, while the power flow among the sub-grids is managed by the ILC. However, in case of parallel connected ILCs, some ILCs operate in VCM in DC sub-grid while some operate in VCM in AC sub-grid.

3) GRID FOLLOWING MODE TO GRID FORMING MODE

During a mode transition of HMG from grid following to grid forming, two types of control approaches are mainly used, i.e., (a) change of power/current control mode in GFWM to VCM in GFM and (b) unified control method. Generally, in power/current control mode, the DGs are operating at MPP by using MPPT to supply the maximum generated energy to UG. Moreover, VCM is used to maintain generation-load demand and supply power to critical loads. In [159], the authors proposed a smooth and seamless mode transition method in which the line current of the DGs is reduced to zero before initiating the mode transition. The authors in [160] proposed a method in which a fast transition is achieved without making the line current of DGs zero. In this approach, a transition is achieved by coordinating current control in GFWM and voltage control in GFM. The transition from GFWM to GFM can also be achieved by using IS detection algorithms such as passive, active, and communication link based detection methods. A smooth mode transition can be achieved by these approaches by selecting a proper mode transition time [161].

In a second approach, a control strategy did not need to be modified before or after the mode transition. Hence, it is a challenging task to develop a control strategy that performs efficiently in GFM, GFWM, as well as during transition [39]. Hence, to cope with this challenge, a unified controller is designed to perform effectively in all operating modes. In this method, the DGs and ESS units with small capacities are operating in CCM, while the DGs and ESS units with large capacities are operating in VCM. However, as a single unified controller, it needed to be operated in GC, IS, and mode transition; therefore, some modifications are needed to perform the control actions effectively. For instance, the authors in [162] proposed a unified controller in which a PI droop is combined with a virtual impedance controller. In [120], the authors proposed a droop control-based disturbance observer to realize a smooth transition. In this method, a disturbance observer is used to track the sudden variation in current and suppress the mode transition impacts.

4) GRID FORMING MODE TO GRID FOLLOWING MODE

Generally, two control methods are used for the transition from GFM to GFWM, i.e., (a) switching of VCM in GFM to power/current control mode in GFWM and (b) unified control strategy in both VCM and CCM. The voltage at the PCC of the MG must be synchronized with the UG before re-connection, which can be achieved by passive or active Synchronization (SYN) method. In a passive SYN technique, MG and UG must have the same phase angle while assuming that they have almost equal voltage magnitude. This method is widely used; however, unequal voltage between MG and UG may cause transients during re-connection. On the contrary, in active SYN method, the phase angle, voltage magnitude, and frequency of the MG must be synchronized with the UG before reconnection. Moreover, it requires the coordination of multiple DGs to attain a smooth reconnection. In some scenarios, a separate SYN unit is required, which is embedded in the MG. This unit acts as an independent entity and provides the signals to attain a smooth reconnection of IS MG back to UG. Moreover, in some scenarios, a SYN unit is embedded in a controller that provide the signals to ensure smooth reconnection of MG, such as the authors in [31] uses a separate control loop that generates the compensation signals for the SC to ensure a smooth reconnection. Furthermore, active SYN can be achieved by using two approaches, i.e., (a) some DGs initiate the SYN process while other DGs follow them and (b) all DGs equally participate in the SYN process. A first approach is used when some DGs in an MG are operating in VCM while other DGs are operating in CCM [163]. In a second approach, all the DGs in an MG are operating in VCM [164].

D. HIGHLIGHTS AND RECOMMENDATIONS

The control and power management of HMG systems are very complex compared to individual AC or DC MGs. Usually single-stage and two-stage ILCs are used to provide a coordination between AC and DC sub-grids in HMG system. Therefore, the stability of HMG mainly depends on the reliable operation of ILCs and is achieved through applied control strategy. Hence, in this section, different control strategies are reviewed and the following findings and research gaps are identified: (a) majority of work related to the ILC control are based on droop methods that provides power management and ensure the system stability; however, due to high penetration of low inertia of RESs based DGs into HMG system, these control strategies are unable to perform the control tasks efficiently [165], (b) charging and discharging control of ESSs with different SOCs is a challenging task a distributed master-slave scheme is used to cope with this challenge however very less concentration is given to the balancing of different SOCs of ESSs, (c) the unified controller of ILC should be designed in a manner that is work in collaboration with the other power converters used in HMG to ensure the efficient and stable performance of overall system, (d) intelligent control schemes such as ANN, FL, etc. can handle the time-varying and non-linear dynamics of the system and learn from the system data to improve the performance, although they are adaptable and durable but they require high computation and training [166], (e) artificial intelligent based supervisory control scheme should be design that ensure power management in IS and GC modes as well as during mode transition to accomplish different control objectives, (f) a coordinated controller based on hierarchical structure can be investigated that can accomplish different control tasks such as power management, economic dispatch; moreover, synchronization and islanded detection units should be the part of the controller [167], [168].

V. PROTECTION IN HYBRID AC/DC MICROGRID

In an HMG, numerous AC and DC energy generating resources are integrated; as a result, numerous challenges arise. Among numerous challenges, protection is one of them that requires attention. Protection of an HMG is very important for the economic and reliable operation. Therefore, in this section, different PCs along with different PSs and protection devices are discussed in detail.

A. PROTECTION CHALLENGES

Different protection challenges that are faced by HMG are discussed below in detail.

1) LACK OF COORDINATION

Due to increased complexity of HMG system, coordination between the AC and DC Protection Relays (PRs) is very important to ensure the security of the network. The authors in [169] proposed a coordination control scheme that mitigates the effects of miscalculated fault characteristics of DGs and ensures the efficient operation of PRs. A coordination control for power converter based DGs is proposed in [170] to enhance the stability margin of HMG. In this work, the oscillations in the waveforms are suppressed by providing reactive power support. Moreover, the resilience and security of HMG is ensured by developing coordination between AC and DC fault PSs.

2) NO DIRECT CONNECTION TO UG

In case of fault on the utility side or mal-operation of the Circuit Breaker (CB), may create a situation when there is no direct connection between the HMG and UG; however, still a portion of the load is connected to the HMG. In this situation, the IS condition is unknown, and some portions of the system still operate in GC mode. Hence, it may cause damage to the DGs as well as sensitive components and may create a dangerous situation for the fault-attending personnel [171].

3) VARIATIONS IN FAULT CURRENT LEVEL

When an HMG operates in a GC mode, a variation in fault current occurs at any instant due to node characteristics, power converters, network configuration, operational characteristics, grid impedance, etc. Moreover, the level of fault current also depends the type of DG, such as the synchronous based DGs contribute more in fault current level compared with the inverter based DGs. Consider a power network presented in Fig. 21. It is assumed that the fault occurs at Bus 5, then in this scenario, DG_1, DG_2, and UG contribute to the fault current, as a result, their level increases. This increment in fault current level has two main effects, i.e., (a) the protection devices are interconnected with each other, therefore, a rise in fault current level may affect the inter-relationship of these devices and (b) during the designing process, the selection of Protection Devices (PDs) is based on the network's short circuit capacity; therefore, a rise in fault current may exceed the network's short circuit limits; as a result, it may exceed the PDs limits and affects its performance [172].

4) BIDIRECTIONAL POWER FLOW

In HMG systems, due to the high integration of RESs based generating units, the power flow is bidirectional; therefore, the PSs that are used in traditional power systems (where the power flow is unidirectional) are failed to perform efficiently in HMG systems [173]. Moreover, the modern HMGs are generally dominated by the RESs based DGs which have very

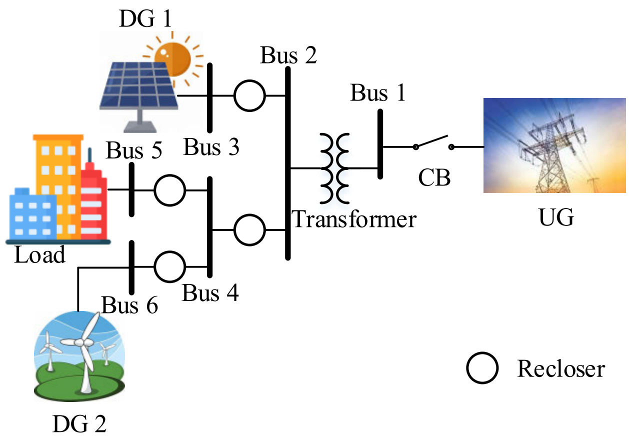

FIGURE 21. Schematic diagram of variations in fault current level.

low or no inertia; therefore, the fault ride through capabilities of the system are also reduced [174]. Hence, to overcome these challenges, unified control schemes are required that coordinate the multi-directional faults according to RESs and timely reclose the line at which a fault occurs before disturbing the whole HMG system.

5) GROUNDING

In a DC sub-grid, two types of faults are generally occurred, i.e., (a) Line-to-Ground (L-G) fault; this fault is occurred frequently and is influenced by grounding system and (b) Line-to-Line (L-L) fault; it has lower fault impedance and can damage the network [175].

There are numerous factors that should be considered while selecting a grounding system, such as the level of touch voltage. Touch voltage is the voltage difference between the energized device and the personnel feet in contact with the device. If the potential difference exceeds a certain value (generally 60 V), it can be dangerous for personnel safety. Hence, by minimizing the intensity of touch level ensure the safety of the personnel [176]. The other factor that affects the grounding system is the stray current. A stray current mainly arises due to the electrochemical degradation of metal due to the reaction of metal with soil [177]. This phenomena usually occurs at locations where the current leaks into the soil; thus, as a result, the current changes its nature from an electronic one in a conductor to an ionic one in the soil [178]. Furthermore, stray current and touch voltage are in inverse relation to each other through ground resistance. For example, a system with solid ground has the highest stray current and the lowest touch voltage. Similarly, in a scenario where a system has a large grounding resistance, the touch voltage is at its maximum value while the stray current is almost zero. Hence, due to the inverse relationship, the stray current and touch voltage cannot be minimized at the same time. Therefore, their optimal values can be attained by designing an optimized and efficient grounding system [179].

A third factor that affects the grounding system is fault detection. The IEC 60364 defines three families of grounding systems by using three codes, i.e., IT, TT, and TN. A first alphabet presents the type of connection between the ground buses and source, and that can either be I (not connected) or T (direct connection). A second alphabet denotes the connection between the network or ground and the device being supplied, and that can either be N (supply network providing the ground connection) or T (direct local connection to the ground) [180]. In a TT grounding system, the fault did not migrate due to high impedance of the fault loop. However, in this system, circulating current and high voltage stress are the main disadvantages. In the TN system, the exposed lines and metallic parts have a common connection to the ground, while in the IT system, the lines are not connected to the ground and only the exposed metallic parts are commonly connected to the ground [181]. Thus, in the TN system, fault detection is simple because of the low grounding resistance; however, in this system, the level of touch voltage may exceed its limits; hence, it can be dangerous for the safety of the personnel. On the contrary, IT system ensures personnel safety because of low fault currents; however, fault detection in these systems is a challenging task [182].

6) CASCADING FAULTS

Cascading faults can be defined as an occurrence that initiates during an anomalous operation of DC sub-grid or in the inverter of AC sub-grid which results in numerous fault situations [183]. This type of fault is frequently occurred in HMG system. Moreover, it can endanger the power quality, safety, and stability of the system; therefore, robust PSs are required to avoid cascading faults [184].

7) ISLANDED CHALLENGES

The integration of RESs into an HMG brings numerous benefits; however, it also creates numerous protection challenges for the system. When an HMG is intentionally or unintentionally disconnected from the UG, it can considerably affect the PSs [185]. During the occurrence of a fault, the respective DG is disconnected; therefore, the PSs must act and update the corresponding protection algorithm [186].

8) FAULTS DURING GC MODE

During normal operation, when a fault occurs on the UG side, it will automatically trip the PDs. In this scenario, initially, the PDs at PCC are tripped, then the PDs of the individual DGs are tripped. Hence, the faulty portion of the system is immediately disconnected from the network by these PDs while the rest of the system performs its functionality. Conditions like voltage unbalance, low voltage, etc. are strenuous and must be identified as they can cause damage to sensitive devices.

9) NATURAL ZERO-CROSSING CURRENT

The operation of CB in both AC and DC sub-grids is based on the arc phenomena. In an AC sub-grid, the mechanism of CB depends on the natural zero-crossing of AC current, enabling them to naturally differentiate the arc within the half cycle after tripping. However, in DC sub-grid or network, the disruption of DC current is a key problem because a DC current lacks natural zero-crossing. This problem not only causes danger to personnel lives but also causes contact erosion of CBs; as a result, the lifetime of the CBs is decreased [187].

10) LACK OF UNIFIED PROTECTION SCHEMES

There is a lack of unified PSs that simultaneously protect the AC and DC sub-grids of the HMG system in case of faults. The literature so far has only focused on AC or DC faults while no consideration is given to combined AC/DC faults [188]. Therefore, a unified controller is required that ensure the reliability and stability of HMG network during AC/DC faults. One of the most challenging problems in HMG systems is designing a PS against short-circuit faults [189]. When a short-circuit fault occurs in the system the magnitude of the current reaches to high level immediately because of the fast discharge rate of DC capacitor. The converters' switches (IGBTs/MOSFETS) were blocked to avoid any damage; however, the fault current is passed through antiparallel diodes (acts as unstable rectifier) which may cause the failure of the whole DC sub-grid or network [190]. Therefore, the PSs must be efficient and robust enough to handle these challenges effectively.

11) RESYNCHRONIZATION

In the absence of DG, if a transient fault occurs, a recloser operates and disconnects its downstream section. However, in the presence of DG, faults are supplied by both the networks and by DG. Therefore, if the recloser disconnects its downstream network, a DG will continue to supply the fault current, and in a condition if the recloser is defective then the transient fault becomes a permanent fault. Moreover, in a scenario where an active UG is connected to the passive network, a conventional recloser can be used. However, in MG scenario, a conventional network cannot be used because of the presence of active networks on both sides (i.e., the connection between HMG and UG); therefore, a properly designed robust recloser is needed [191].

12) FALSE TRIPPING

False tripping in a feeder takes place when the DG of the neighbouring feeder produces a fault current that causes an increment in the level of short circuit of the current feeder. The healthy section of the network will be deactivated because of the fault in the neighbouring feeder. In such scenarios, the PDs of the neighbouring feeder may disable the circuit. Let consider a scenario (as shown in Fig. 22) in which a fault occurs in substation B and no DG is connected to feeder 1.

Then, in this case, feeder 1 will not contribute any fault current, and only UG will contribute to the fault current. Hence, it can be said that the fault is clear by relay B while relay A did not contribute. On the contrary, consider a scenario, when DG is connected to feeder 1, then it will contribute a maximum

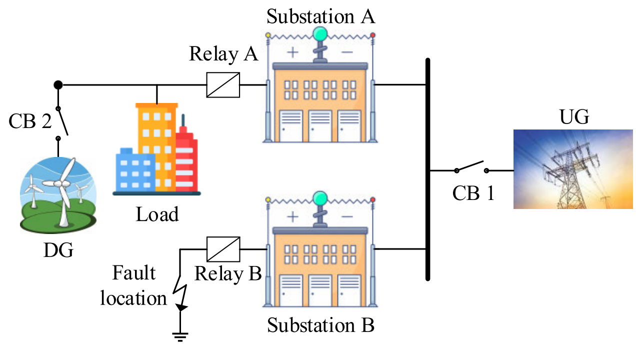

FIGURE 22. Schematic diagram of false tripping.

fault current; as a result, the current value in substation A is greater than the rated value of relay A. Hence, relay A will be tripped before relay B, and thus phenomena is known as false tripping [192].

13) INTERSYSTEM FAULTS

An HMG system consists of AC/DC distribution and transmission networks; therefore, the lines face galvanic and electromagnetic challenges. Hence, the interaction of these two lines (i.e., AC and DC lines) results in a fault, which can be referred to as an intersystem fault [193]. Traditional protection cannot overcome these faults in HMG networks; therefore, robust and intelligent control and PSs are required to clear this type of fault.

14) MALFUNCTIONING OF DISTANCE RELAY

A distance relay is used to clear the faults within its permissible distance. The distance between the relay and the location where a fault occurs mainly depends on the maximum impedance. During fault conditions, in a scenario when DG is not connected, then the calculated impedance is less than the impedance set value. Hence, in this scenario, a distance relay effectively clears the fault. On the contrary, in a scenario when DG is connected, then a rise in voltage increases the calculated value of impedance than that of the set value. As the value of impedance increases, the fault distance also increases linearly. Hence, this condition may affect the operation of the relay, and maybe the fault cannot be clear by the relay which is in its specified zone.

B. PROTECTION SCHEMES

To cope with the challenges discussed above, numerous protection techniques have been proposed recently in the state-of-the-art literature. Different protection schemes that can possibly be used in HMG networks are presented in Fig. 23 and are discussed below in detail.

1) CONVENTIONAL PROTECTION SCHEMES

Numerous techniques have been used to ensure the power system's protection in case of any fault. These schemes use an oscillation pattern, magnitude, and rate of change of current

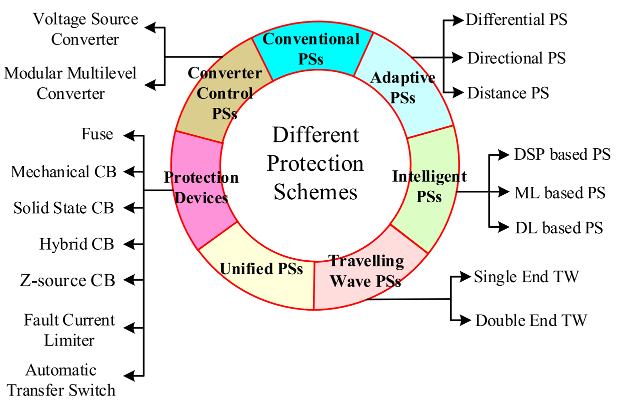

FIGURE 23. Different PSs in HMG.

to locate and identify the fault. The authors in [194] use first and second order current derivatives to protect the distribution lines in a DC system. Based on local measurements, the threshold derivative is calculated, and when the fault transient exceeds the criteria, the protection algorithm comes into action. The conventional schemes proposed in [195] operate on the basis of predefined threshold values, which are derived from the operational condition of the network. These schemes perform effectively in both DC and AC networks; however, they cannot perform effectively in case of HMG systems due to the different natures of DC and AC faults and multiple directions of power flow [196]. The conventional PSs can only be applied to either DC or AC networks, not to DC and AC simultaneously; hence, they have very limited applications in the HMG system.

2) Adaptive Protection Schemes

An adaptive PS can be defined as an online system that adjusts the parameters of the PS according to any system's disturbance through externally generated signals. Adaptive PSs can be divided into three categories, i.e., differential, directional, and distance.

The operation of differential PSs is based on the comparison of current measurements of relays which are installed on both sends of protected device (such as line, bus bar, transformer, etc.). In case of any fault, if the difference between the measured currents exceeds a predefined threshold value, then the relays perform and disconnect the faulty device from the network. Furthermore, backup protection can also be provided for the device by adjusting the downstream and upstream relays [197]. The authors in [198] proposed a differential PS in which a conventional over-current relay is used along with Communication Network (CN) to protect an MG consisting of both synchronous generator and inverter based DGs. However, this method lacks to provide protection under un-balanced load condition. In [199], the authors designed a differential based PS by using Phasor Measurement Units (PMUs) and digital relays along with CN. Although, this method provide protection against high impedance faults, however, it is economical not very feasible due to high cost of PMUs. Another differential based PS was proposed in [200] to protect the meshed HVDC network. This technique uses the current values and a differential threshold criterion which is based on external and internal faults. The authors in [201] proposed a current differential PS for PV based DC MGs. This technique uses a cumulative average method to detect faults. The above discussed PSs are vulnerable to fluctuating impedances and fault levels in HMG system. Therefore, to make them feasible for HMG networks, back propagation method may be need that significantly increase the size and cost of the protection system.

A directional PS that uses frequency impedances is proposed in [202] for modular multi-level converters in HVDC systems. This technique is independent of line boundary of devices. The authors in [203] proposed a directional technique based PS that uses the transient fault current of both end sides to detect the direction of fault. This scheme uses Travelling Wave (TW) characteristics to distinguish backward and forward faults on DC bus. The authors in [204] proposed a current directional PS that uses frequency parameters to cope with the distributed capacitance effect that occurs in current differential techniques. In this method, the faults are identified by using ratio of high and low frequency energies of differential current.

The authors in [205] proposed a distance PS by using the current and voltage data from the distributed network. This technique efficiently locates the location of the fault. Similarly, the authors in [206] proposed a distance PS that locate the fault location in DC network by using relay coordination. This method lacks to accurately locate the fault distance; however, accurate calculation of distance is very important for the coordination between the circuit breakers in a meshed network. The authors in [207] proposed a PS for Single Phase Grounding (SPG) faults that occurs in Modular Multi-level Converters (MMCs) based HMG system. An SPG fault causes over current at MMC terminals and voltage imbalances in active networks. The authors in [208] proposed a PS that detection and accurately locate the fault in DC and AC distribution network.

3) UNIFIED PROTECTION SCHEMES

The interactions between AC and DC sub-grids in HMG system increase complexity to the protection scheme. Numerous robust control strategies have been designed to protect HMG system. However, due to different characteristics and nature of AC and DC on a single network, a unified PSs is required along with the adaptive schemes to ensure the security of the network. Hence, the authors in [209] proposed a unified impedance based relay scheme to protect the HMG network in case of fault. This technique efficiently detects both AC and DC faults using the proposed relay that have high reliability and efficacy. Beside these advantages, a main limitation of this technique is its high dependency on the threshold criteria and relays to differentiate between the non-faulty and faulty events. Moreover, during high impedance faults the performance of the PS can be affected. Similarly, the authors in [210] proposed a unified PS that ensure the protection of AC and DC hybrid networks by establishing a coordination between AC and DC protective relays. However, this technique requires a CN to coordinate among AC and DC relays.

4) TRAVELLING WAVE PROTECTION SCHEMES

A fast protection of AC/DC HMG networks can be ensured by using TW techniques. TW protection is preferable to employed in long transmission lines and high voltage applications due to its high speed. The TW schemes are generally categorized into Single End (SE) and Double End (DE) [211]. The authors in [212] comprehensively study the TW based fault location methods, which are un-affected by operating mode of the system, equivalent impedance, and grounding resistance. Similarly, the authors in [213] presented a TW based rapid fault identification method whose response time is independent of inductor saturation, power fluctuation, and distributed capacitance. As a result, TW based scheme enhance the protection of HMG networks.

The authors in [214] proposed a discrete wavelet transform PS based on SE-TW for overhead lines of HMG network. This PS includes all intersystem, AC, and DC fault scenarios and efficiently protect the HMG network. The authors in [215] presented a TW based PS that uses the TWs' refraction wave to distinguish between fault and non-fault cases. Moreover, the location of fault can be determined by using teager energy operators and symmetric mode decomposition. In [216], an improved DE-TW based PS was proposed to protect two terminal DC network. This PS uses a step response which includes the frequency dependent characteristics in the network.

The SE-TW and DE-TW techniques shows high vulnerability to inaccuracies during the arrival time of TW. Although TW based PS perform very efficiently; however, there are some disadvantages such as DE based PS needs CN for sampling to avoid time delays, demand for high sampling rate for diagnosis of fault, and selection of extraction algorithm.

5) CONVERTER CONTROL PROTECTION SCHEMES

Due to high integration of RESs into HMG, a significant advancement in power converter topologies and control has been made in recent years. Therefore, beside conversion, power converters are also used to provide protection against faults.

The inverters are mainly used for AC to DC inversion and are categorized on the basis of its operating mode as Voltage Source Converter (VSC) and Current Source Converter (CSC). In power system applications, the VSCs are widely used as compared to CSCs due to their compact design and ability to control and protect MGs efficiently [217], such as the authors in [218] proposed cascaded two level VSC with multiple block cells having a main objective to attain high quality output waveforms. In [39], a synchronization controller is designed for the VSC based MGs. This controller ensures seamless synchronization as well as also provide protection to MG during the transition from GC mode to IS mode. The main drawbacks of VSCs are that they are not able to protect a system under high stress fault conditions which may lead to system instability.

Compared to VSCs, when MMCs are used in HMG systems it offers numerous advantages such as high harmonic suppression, highly modular design, easily scalable, low switching frequency devices, etc. [219]. MMC based HVDC networks have been developed extensively as it provides easy integration of large scale RESs based DG units, power supply to passive networks, and interconnection of regional grids [220]. Hence, it leads to high demands for fault separation as well as protection; including reliability, stability, and prompt detection. In [221], the authors proposed a PS for MMC based DC network. In this scheme, the authors' use the reverse blocking of IGBTs that clear the faults with fast response. There exist three types of MMC, i.e., Half Bridge (HB), Full Bridge (FB), and Clamped Submodules (CSM). HB-MMC are not feasible for HMG protection applications as it not able to cope with the DC fault current limitation. On the contrary, FB-MMC and CSM-MMC with the addition of extra circuitry make them capable to self-clear the current fault [222]. The authors in [223] proposed a FB submodule based MMC PS that limits the fault current by using the inbuilt capability. Similarly, the authors in [224] uses CSM based MMC for the protection of HVDC networks. A submodule based MMC to protect the system in case of short circuit fault is presented in [225]. A main disadvantage of MMC based PS is that MMC is vulnerable to voltage stresses owing to over-current and over-voltage during faults. Moreover, fast PS is also required to protect MMC; furthermore, due to presence of numerous sub-modules the complexity and cost is considerably increased.

6) INTELLIGENT PROTECTION SCHEMES

Different intelligent PSs are reported in literature that can be broadly classified in three categories, i.e., Digital Signal Processing (DSP) based PSs, Machine Learning (ML) based PSs, and Deep Learning (DL) based PSs.

Numerous DSP based PSs for HMG networks are presented in a literature that ensure the stability and reliability of the system. Short Time Fourier Transform (STFT) based PS was proposed in [213] that uses the high frequency components of transient of AC as well as DC faults. This scheme effectively protects the AC and DC networks during faults. Similarly, the authors in [226] presented an STFT based PS that provide protection against high frequency transients to MMC based networks. Moreover, in this scheme, low sampling frequency is used to detect high impedance faults. In [227], un-decimated wavelet and Mathematical Morphological Gradient (MMG) methods are used to detect the arrival of faulty waves on both end terminals. As in this scheme the data of both terminal ends are uses therefore a fast CN is needed to avoid any delay under fault conditions.

The authors in [228] uses a modified MMG method to differentiate among negative and positive polarity and provide protection to the distribution network by using transient energy signals. In [229] Hilbert Haung (HH) method is used to detect the arrival of voltage travelling wave. In this scheme the distance between the location of the fault on transmission line and converter is computed and perform the mandatory actions to protect the network. Similarly, the authors in [230] also uses HH method to provide protection to VSC based DC network during faults. These schemes eliminate the steady-state ripples within a defined range of frequency and uses the energy density level to identify the faults. However, these methods are highly dependent on the precise information of fault current; moreover, these frequency domain methods are also very sensitive to measurement inaccuracies and noise. DSP PSs considerably mitigates the protection challenges in HMG networks. However, it requires high computation time and sampling frequency to cope with the transient nature of converter topologies and DGs (PV, wind, etc.). Moreover, due to different natures of faults in HMG network, it is a challenging task to identify the unfaulty and faulty events by using DSP methods.

ML PSs have considerably enhanced the protection mechanism is power networks. Most of the literature so far either deals with DC faults or AC faults; therefore, a unified protection scheme of HMG is needed. The authors in [231] proposed a unified PS that uses a combination of ML and DSP techniques to provide protection to HMG network during faults. In [232], the authors presented a K-means clustering technique to precisely identify the location of fault by using subsets of Digital Fault Recorder (DFR) for HMG transmission lines. A discrete wavelet transformation based PS that uses undirected graph is used to extract the coefficients and determine the arrival time. The location of fault is accurately determined by this PS in both AC and DC networks. The authors in [233] uses a multiclass AdaBoost and morphological operator algorithms to provide protection to HMG network during faults. Moreover, in this method, the noise in eliminated by using opening-closing difference operators and dilation erosion. These features of these operators are optimized using Kurtosis method. The optimized data is then used by an algorithm to classify and detect the faults. The effectiveness and efficacy of ML algorithms in HMG networks mainly depend on the selection of an algorithm and the volume of training data. Moreover, due to different characteristics and nature of complex HMG network, the ML techniques are unable to extract the intrinsic nature of disturbances and faults.

DL based PSs are very effective to address the protection challenges in power systems due to its ability to detect the intrinsic nature of disturbances and faults [234]. The authors in [235] proposed a PS in which Convolutional Neural Network (CNN), soft classifiers, and auto-encoders are utilized to protect MMC based DC network. In this method, the upper and lower bridge currents along with the AC-side current are used to train the algorithm; thus, as a result, high accuracy can be attained. In [236], a linear regression method based on convolutional network is used to protect and detect the fault location in back-to-back MMC based networks. In this scheme, the current and voltage data are obtained from one single end, and the algorithm will learn the future trends automatically. The authors in [237] proposed a deep CNN based method to identify and accurately detect a fault in MMC based networks. In this scheme, the voltage signals are initially normalized and transformed them into image recognition data, which is then used to train a model. In [238], a 1-D CNN PS is proposed that avoid the blockage of MMC submodules. This PS ensured the stability and security of the system and is independent from any feature extraction step. The authors in [239] used an intelligent multi-agent management scheme that uses reinforcement learning to protect HMG network. The complexity of DL and the requirement to train a large dataset has hindered the effectiveness of DL in protection HMG networks.

C. PROTECTION DEVICES

Numerous devices have been reported in a literature to protect the power system such as fuse, Mechanical Circuit Breaker (MCB), Solid State Circuit Breaker (SSCB), Hybrid Circuit Breaker (HCB), Z-source Circuit Breaker (ZCB), Fault Current Limiter (FCL), and Automatic Transfer Switch (ATS). These protection devices are discussed below in this subsection.

1) FUSE

When a large current flows through a fuse, a metal wire in a fuse melts down and thus disconnect the downstream circuitry. Fuse are able to operate in AC as well as in DC networks. Main advantages of fuses are its simple operating principle and cost effective. However, they are not very feasible for HMG networks, as fuses are not able to distinguish among type of fault, i.e., transient or permanent [240].

2) MECHANICAL CIRCUIT BREAKER

The safety of DC sub-grid or network is significantly enhanced with the development of MCB. The on-state resistance of MCBs is low, however, the opening speed is often low [241]. An artificial zero crossing point is generated in MCBs by turning on the resonance circuit, thus allowing the flow of current through them [242]. The authors in [243] describe the operation and function of fast mechanical switch. A fast MCB for hybrid AC/DC MG is presented in [244] that facilitate the MCB interruptions within 2-3 millisecond.

3) SOLID STATE CIRCUIT BREAKER

SSCBs are emerged as an alternative to MCBs and shows fast response during transient events [245]. Compared to MCBs, SSCBs have fast operating speed thus they provide effective protection against faults, as a result, enhances the robustness of the system [246]. The authors in [247] uses a SSCB along with the fault current limiter to provide protection to system

TABLE 8. Comparison of different protection schemes.

Scheme	Type	Complexity	Reliability	Communication Requirement	Coordination Schemes	Sensitivity	Fault Detection	Threshold Need	Cost
Conventional	Overcurrent	Low	Low	No	Low	Intermediate	Slow	Yes	Low
Adaptive	Distance	Low	Low	No	Low	High	Slow	Yes	Low
	Directional	Low	Low	No	Low	Intermediate	Slow	Yes	Low
	Differential	Low	Low	No	Low	High	Slow	Yes	Low
Converter Control		Low	Moderate	Moderate	Moderate	High	Moderate	Moderate	Moderate
Unified		High	High	Yes	High	High	Fast	Moderate	High
TW		Low	Moderate	Yes	Moderate	Intermediate	Fast	Moderate	Moderate
Intelligent	DL	High	High	High	High	High	Fast	No	High
	ML	High	High	High	High	High	Fast	No	High
	DSP	High	High	High	High	High	Fast	Yes	High

against faults. In this method, a traditional threshold scheme is replaced by intelligent decision tree that train the model for the identification of fault. In [248], SSCBs are combined with numerous intelligent relays to identify the DC faults. This method provides protection from tripping within a time slot of sub-millisecond. The authors in [249] uses a SSCB with self-adapted current limiter for LVDC networks. This scheme responds effectively and limit the faults with proper coordination.

4) HYBRID CIRCUIT BREAKER

HCB is a self-contained system that consists of three functional components; i.e., (a) Load Commutation Switch (LCS), breaker, and Ultrafast Disconnector (UD) [250]. HCBs are capable to interrupt the abnormalities of current in a steady-state as well as during faults. Moreover, HCBs have fast response, reliable, robust, and low loss breakers. HCBs have an advantage over MCBs and SSCBs because it is equipped with advanced and intelligent control algorithm that make them more efficient and their operation more dynamic [251]. The authors in [252] proposed a PS in which HCB and MMC are used to protect DC networks. The main disadvantage of this scheme is its high losses and cost. In [253], an HCB is designed in which SSCBs and MCB are combined to cope with the arc-less current commutation in dump resistor. This method reduces the time of current commutation and number of components count.

These breakers are the specialized type of SSCBs. A primary difference between ZCB and SSCB is that it does not depend on the fault detection circuitry and has the ability to handle the transients more effectively. Moreover, in ZCBs, coordination is not required in large systems that involves multiple breakers (either in parallel or upstream) [254]. However, besides these advantages there are some limitations of these breakers such as compared to SSCBs these breakers need passive components that caused an increment in mass and volume. Moreover, they also do not effectively respond to long-term arc faults [255].

5) FAULT CURRENT LIMITER

FCLs are usually installed near to Point of Common Coupling (PCC) to handle the internal as well as external faults. In case of faults, the impedance value of FCL is kept at high values in order to avoid or limit the excessive fault current; whereas, in normal operation, the impedance is set to low value to avoid losses [256]. The main disadvantages of FCL includes its expensive installation cost and its coordination with other devices is not very effective.

6) AUTOMATIC TRANSFER SWITCH

ATS has the ability to transform the framework to ensure an uninterruptable and continuous supply to healthy part of the network. During fault condition, it activates all the DGs (backup DGs) to complete the demand of the loads [257]. A main disadvantage of ATS is that it requires all the switches and CBs to perform the reclosing operation before an ATS starts its operation.

D. HIGHLIGHTS AND RECOMMENDATIONS

In this section, different protection challenges related to HMG system are highlighted. To overcome these protection challenges different protection schemes are devices are comprehensively reviewed. A comparative analysis of different reviewed protection schemes is presented in Table 8. Moreover, the features and limitations of different protection devices are summarized in Table 9. Based on the above-discussed literature some highlights and recommendations are given as: (a) require to design robust and fast relays that perform effectively in hybrid networks, (b) protection algorithm should involve the fault characteristics of both AC and DC faults and the parameters should be adaptive to handle uncertainties, (c) HMG networks have high grounding protection challenges, therefore, a grounding scheme with high impedance are feasible to mitigate the high fault current effects, (d) due to discharge of capacitors a fast rise in DC fault current is observed therefore the blocking capability of the converters should be consider while developing a PS for

TABLE 9. Features of different protection devices.

Protection Devices	Features	Limitations
Fuse	• Simple framework • Cost effective • Operating principle is based on melting of metal wire when large current flows through it • Its applications are limited to either AC or DC network	• Unable to differentiate between transient and permanent faults • Not appropriate for HMG systems
MCB	• Resonant circuit include active and passive circuits which reduce the zero-crossing problem • Cost effective • Interconnection of mechanical switch, communication circuit and energy absorber circuit	• Limited capability of fault current disruption • Stagnant response characteristics
SSCB	• Fast dynamic response • Presence of semiconductor devices such as IGBT, IGCT, GTO	• High power losses • High cost • Inclusion of filter for electromagnetic interference • Require dv/dt and di/dt control
HCB	• Fast response • Low power losses • Combine the advantageous features of MCB and SSCB • No arching	• High cost • Require a mechanical switch with low conduction losses and fast response
ZCB	• Compared to SSCB it has low cost • Capable to handle the transient component • Automated isolation	• Not provide the protracted protection • Require large transient fault for activation
FCL	• Located near the PCC to handle both internal and external faults • During normal condition the impedance setting are kept at low value to avoid the losses • During fault condition the impedance setting at kept at high value to limit the fault current	• Coordination problem • High cost
ATS	• In case of fault, it activates the backup DG to meet the load requirement • Ability to recompose the system in order to ensure the continuous power supply to healthy part	• Require to perform all reclosing operation before the initiation of ATS operation • Required time delay

VSC and MMC based networks, (e) to limit the abnormal current, FCLs should be used before triggering the relays, (f) due to integration of multiple DGs in HMG system, its protection cannot be ensured without the use of CN; therefore, a CN with noise-free interface is needed to enhance the system security and avoid false tripping of CBs, (g) communication less protection schemes such as conventional and adaptive techniques are unable to overcome the protection challenges efficiently due to high penetration of DGs and loads, (h) a coordination between PSs, converters, and controllers must be robust and reliable to ensure the protection of HMG network, (i) the harmonic contents that arises due to non-linear components of HMG network must be filtered out to avoid the malfunctioning of relays, (g) TW based PS are frequently used in power system; hence, a coordination of TW with relays and controllers can cope the protection challenges in HMG network, (k) more improvements (in term of detection time) should be made in AI based PS and need to develop a robust centralized monitoring system with multi-agent based control algorithm, (l) the integration of PMUs to observe the events in AC network and develop a coordination based algorithm with the network with the help of communication network in order to protect the HMG network is recommended, (m) cost-effective communication network with latest protection infrastructure should be implemented for system control, energy utilization, and data transfer, (n) coordination of TW based algorithm with the relays and the controller can cope with the protection challenges in HMG system, (o) to ensure the independency of HMG a decentralized backup protection system is very important that identify the defect when communication or main protection system failure occurs, (p) to determine the effectiveness of protection scheme, real-time experimentation is needed that ensure its efficacy in the practical situations.

VI. CONCLUSION

Hybrid AC/DC MG is one of the main elements in realizing the smart grid, as it can integrate both AC and DC loads and resources and facilitate the reliable and efficient operation of the smart grid. This manuscript comprehensively reviewed the power converters, interconnection methods, control, power management, and protection of HMG. In this work, initially, an MG is classified into seven different groups based on their configuration, application, location, scenario, generating source, control, and size, and a detailed discussion on every classification is presented. Moreover, a comprehensive review on different operating modes of the converters and different interconnection methods used in HMG is presented. It can be concluded that besides single-stage and two-stage ILCs; SSTs, ERs, and small-scale FACTS can be used for the interconnection of different sub-grids in HMG system. This study also focused on the primary, secondary, and tertiary control levels of the hierarchical structure and presented a detailed review of different control strategies applied to these control levels to attain different control objectives. Moreover, different control strategies for ILC are also discussed. Furthermore, different control methods that ensure accurate power management in different operating modes of the HMG, including the mode transition, are presented. Moreover, as protection of the system is the main important factor; therefore, this manuscript also focused on the protection challenges of HMG. Based on the fault protection mechanism, the protection schemes are classified, and a detailed review of existing protection schemes and their applicability in hybrid fault scenarios is presented. The modern intelligent controllers such as ML, DSP, DL, etc. can achieve the control objectives and ensure an uninterruptable power supply to the end-users. Therefore, coordination between the control and protection schemes is very mandatory to avoid blackouts, especially in large HMG networks where multiple and different natures of DGs and loads are interconnected. This research work will pave the way for academic researchers, power industry, and policymakers to understand the interconnecting methods, control, power management, and protection aspects for HMG and assist them to improve the reliability and stability of the future HMG.

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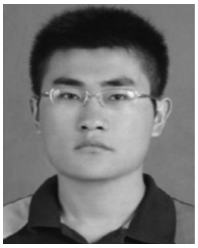

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