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Recent Contributions, Future Prospects and Limitations of Interlinking Converter Control in Hybrid AC/DC Microgrids

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ABSTRACT This work analyzes interlinking converter control in hybrid AC/DC microgrids. The paper addresses the state-of-the-art general hybrid microgrid structure. The key power electronics topologies are used as bidirectional interface converters in the AC and DC parts. Different control structures of hybrid microgrids are categorized, followed by the classification of the main control functions, their control strategies, and the control techniques and a summary of their positive and negative aspects and applications. Control functions, strategies and techniques are classified in the interlinking-converter based. Finally, overall control objectives, time-scaled control structures, and their strategies are outlined. The prospects, main challenges, research gaps, and the trend of the hybrid microgrid structure and control are reviewed and summarized in the conclusions.

INDEX TERMS Bidirectional interface converter, control objectives, distributed generator, droop, hierarchical control, hybrid microgrid, island detection, power-sharing, power quality.

NOMENCLATURE

BIC	Bidirectional Interface Converter
CCS	Continuous Control Set
CM	Common Mode
CSC	Current Source Converter
DG	Distributed Generator
DM	Differential Mode
DS	Distributed Storage
EMC	Electro-Magnetic Compatibility
EMI	ElectroMagnetic Interface
FCS	Finite Control Set
FLC	Fuzzy Logic Control
GTO	Gate Turn-Off thyristor
IC	Interface Converter
ID	Islanding Detection
MG	Microgrid
MMC	Modular Multi-level Converter
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
NDZ	Non-Detection Zone
PCC	Point of Common Coupling
PID+R	Proportional Integral Derivative + Resonant Controller
PWM	Pulse Width Modulation
P2P	Phase to Phase
ROCOF	Rate Of Change Of Frequency
SCADA	Supervisory Control and Data Acquisition
SOC	State Of Charge
SST	Solid State Transformer
SVM	Space Vector Modulation
THD	Total Harmonic Distortion
VSC	Voltage Source Converter
VSG	Virtual Synchronization Generator

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I. INTRODUCTION
Microgrids (MGs) have gained more attention in the past decade since they provide the facility for the exploitation of Distributed Generator (DG) to satisfy the growing rate of electricity demand. With improvements in technology, the share of electricity in global energy demand has increased from 17% in 2000 to 22% in 2018. Also, the electricity consumption growth rate of 80-90% is estimated in 2050 compared to 2018 [1]. Fig. 1 presents the global statistical data of electricity resources in 2018. More than 78% of electricity resources are coal, gas, and oil that produce greenhouse gas and air pollution, as shown in Fig.1. For this reason, the trending usage of DGs in the power grid is justified. The growing rate of electricity demand, lower efficiency of the available power grid, and decreasing cost of the DG technology (PV and wind), with greenhouse gas regulation issues, motivate humans to upgrade the traditional power system to the smart grid through MGs [2].

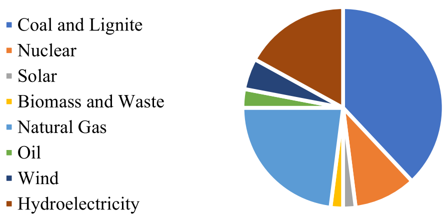


FIGURE 1. Share of electric power generation by resources in the world, 2018 [1].

On the other hand, developments in the power semiconductor technology have opened a new door of power-electronics applications in the power system. Digital signal processors in the control of Interface Converters (ICs) enhance their control algorithm complexity by decreasing the processing time [4]. The power-electronics ICs enable MGs to utilize and control the intermittent generated power of DG, typically with integrated Distributed Storages (DSs) [5]. Each MG consists of different DGs, loads, and DSs, which are connected through controllable ICs. This specification elevates MG functions acting as a controllable entity in the grid-tied or islanded operation mode. When an MG is connected to the main grid, it operates in the grid-tied mode and when it works standalone, it is in the islanded operation mode. Also, MGs can act as a consumer or a generator or a "plug and play" system [3], which provides a lot of freedom in the power system operation.

The increasing rate of DC sources and loads is a strong motivation to shift from mainstream AC MGs to hybrid or DC MGs. However, the AC nature of the existing power system promotes the hybrid MG concept as the first candidate since it is more compatible [3]. AC, DC, and hybrid MGs are different in their common links, which can be divided into three types: AC, DC, and the combination of both [6]. AC MGs are the most common types since they are compatible with the existing grid [3]. Synchronization issues, circulating reactive power, and bigger power losses are their disadvantages. DC MGs attributed to future generations are gaining popularity because of the growing number of DC sources and electronic loads, e.g., PV panels, computers, cellphones, and batteries.

Although the existing distribution grid needs more modifications and higher investment costs, DC MGs are more reliable, efficient, and easier to control. Absence of synchronization issues, lower power loss of reactive power circulation, fewer required power-electronic-converter stages are the merits of DC MGs [6], [3]. But the non-zero crossing nature of the DC current is a challenge in DC breakers. DC MG topologies are described in detail in [7], [8].

However, due to the AC structure of the available power system, a hybrid MG has more potential to be adjusted to the current power system and leverage advantages of both AC and DC MGs [3], [9]–[15]. As some converters are omitted in the hybrid MG structure, the power loss of conversion is reduced and the power quality is increased [13]. The hybrid MG is a complex multi-objective system. It involves a variety of aspects of control, metering, communication, and protection, which have direct influence on other structures affecting each other.

The limitations of utilization of power electronics in hybrid MGs have not been reviewed in detail. This paper gives a comprehensive overview of the control issues of power-electronics devices inside hybrid MGs at the distribution level. In this regard, the incentive is to cover the entire range of various control aspects of power electronics devices in the MG application. In summary, the control studies of the hybrid MG have not addressed the power electronics state of the art. Neither have the objectives of the hybrid MG as a complex control system been reviewed in general terms. The aim of this review paper is to provide a comprehensive classification and comparison of control strategies and techniques in the hybrid MG, taking into account the state of art power electronics limitations and the feasibility of the existing methods for practical application.

The rest of the paper is organized as follows. Section II presents a common hybrid MG structure and different BIC topologies of the hybrid MG regarding power electronics units; in section III, different control structures are analyzed. Different control strategies with their techniques are discussed in section IV. Finally, prospects and conclusions are addressed in sections V and VI.

II. TOPOLOGIES
In most studies of BIC control, the hybrid MG is divided into three zones: AC sub-MG, DC sub-MG, and the Point of Common Coupling (PCC) to the main grid [10]–[12]. AC sub-MG consists of AC-link, DGs, DS, and loads connected to the AC-link. DC-link connected DGs, DSs, and loads from the DC sub-MG. The ICs among AC and DC sub-MG must be bidirectional to permit energy flow in both directions between AC and DC. In some studies, a separate DC-link is proposed for DSs (as LVDS side) to provide a DC-link slack. This extra DC-link enhances the voltage stability in the MG [16].

Different interface structures regarding connection among these three (or four) links have been reported. The most common topologies of AC/DC (between AC-link and DC-link) and DC/DC (Between two DC-links) converters are shown in Fig. 2. A simple 3-phase full-bridge BIC is a popular AC/DC topology presented in Fig. 2. In some studies, a non-inverting DC/DC buck-boost converter is also added to improve the DC-link controllability.

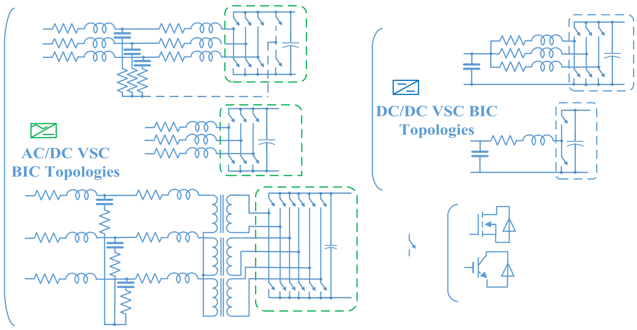


FIGURE 2. The common AC/DC and DC/DC BIC topology.

According to the literature, the PCC voltage level changes from medium levels (between 1 and 35 kV, based on the IEC 60038 [17]) to low voltages (between 100 and 1000 V, based on the IEC 60038 [17]), which is equal to the AC sub- MG voltages.

For a PCC with a medium-voltage-level power transformer, a Solid State Transformer (SST) and cascaded structures are the main options to step down the voltage. The power transformer can be added at the PCC to the main grid, which increases the reliability, leakage current inhibition, and protection degree of both the MG and the main grid through galvanic isolation from each other [18]–[21].

Providing galvanic isolation by a power transformer or high-frequency transformer helps to decrease the flowing leakage current of Common Mode (CM) voltages [18]. Besides, PVs are one of the most cost-effective and widespread resources in MGs and they have parasitic capacitors resulting in CM current. This leakage current produced by high-frequency CM voltage leads to high power loss, lower quality of grid current, ElectroMagnetic Interference (EMI), and other safety issues [20]. Moreover, for large leakage currents, the hybrid MG may trip due to ground current or fault protection [21]. As a result, this leakage current is targeted to be minimized. The two solutions are a bulky low-frequency transformer and a complicated modulated high-frequency transformer in SST. However, their cost, size (especially in residential and commercial applications), and low efficiency (for transformation level) are the main reasons why researchers are seeking transformer-less BIC solutions [18].

The industrial solution for PV arrays is to be equipped with line-frequency (power transformer) or high-frequency transformer at PCC since they isolate PV's parasitic capacitors path (parasitic capacitors between the PV and the ground) through which leakage current can flow [19]. Regarding CM voltage reduction, different topologies such as H5, ... H8, neutral point clamped (three-level full-bridge) are introduced mostly to the inverter mode for PV applications with parasitic capacitors [18], [22]–[24]. In the solutions suggested, the common base topology is the full-bridge Voltage Source Converter (VSC). Then, different configurations of leakage-current blocking switches are added to separate AC and DC side during the freewheeling period [18], [25]. The virtual-ground connection was introduced by [26] and [27] for PV application; however, the proposed topology can be extended in hybrid MGs utilization as well. In this study, the neutral point of the LCL filter is connected to the neutral point of the DC-link capacitor and the neutral point of the three-phase three-level full-bridge inverter. This approach does not change the CM current; however, providing an alternative predominant capacitive path for the CM current decreases the high-frequency CM current flowing by the ground path. The main demerits of this method are the safety issue and the total power-loss increase because the virtual ground path consists of switches [27]. CM solutions are shown with a dashed line in Fig. 2.

Transferring AC power to DC power in one-phase AC/DC BICs provides a double line frequency ripple on the DC side [28]–[35]. This low-frequency ripple power increases the power loss and can decrease the DC sources, ES, and DC-link capacitor life [31], [35]. Moreover, to buffer this ripple power, a large size of the electrolyte capacitor is required; however, these capacitors are sensitive to temperature [36]. As a result, this ripple power increases the power loss in the capacitor and decreases the system reliability by gradually destroying the capacitor. Film capacitors can tolerate higher temperatures but their capacity is not high enough. So, one solution is to separate this ripple power from the constant one. Although different buffering solutions (active and passive methods) have been suggested in different studies [28]–[36], this issue is not entirely solved.

DC isolation and different DC voltage levels are achieved through SST implementation. These topologies need more complex modulation and control methods. It is also possible to increase the transferred power by using more BICs in parallel or different MG configurations. An interleaved buck-boost converter is another solution reported in [15] and [37]. In these studies, to provide different DC bus voltages connected to the common DC-link, a DC/DC n-phase interleaved BIC is presented. Reduction in the DC current-ripple with this interface structure leads to a decline in the required DC capacitor; however, adding an extra DC/DC power electronic level with its required filters results in a higher cost.

BIC can be divided into AC/DC and DC/DC parts to control both AC and DC buses. VSC or Current Source Converter (CSC) are the two main candidates as AC/DC BIC. The priority in MG control is to provide stabilized voltage in the islanded operation, which is promoted by the BIC appliance. As a result, most studies have concentrated on VSCs for MG's interface structure, as shown in Fig. 2. On the other hand, DC side ripples in CSCs and the resulting AC side harmonics make CSCs less popular in the interface structure appliances. To solve this problem, efficient modulation [38] and the control method [39], [40] have been proposed.

On the other hand, the allowable configuration of short circuit switching and inherent current-limiting nature of CSCs and their reliability are shifting researchers' attention to using them for PV [67]–[70], wind [71], or Fuel Cell [72] interface with the main grid.

TABLE 1 categorizes previous studies based on their BIC interface structures, merits, and limitations of each structure, AC and DC voltages. Default voltages are phase-to-phase and phase-to-ground voltages denoted as P. Those BICs without the capability of islanding and fault isolation of the hybrid MG should be equipped with a circuit breaker or static transfer switch at PCC [73].

As shown in TABLE 1, the study in [41] proposes the back-to-back CSC between two MGs. It suggests an optimized Space Vector Modulation (SVM) to reduce the required DC-link inductance. In this study, the pulse patterns of rectifier and inverter CSCs are selected to minimize their voltage differences. The result confirms the lower DC-link ripple current at the expense of more complicated modulation and higher processing time. TABLE 1 shows that in the case of PCC with low AC voltage and a unified DC-link voltage level in hybrid MGs, the majority of studies suggest back-to-back or one full-bridge VSC in the non-isolated condition and with a line frequency in the isolated condition. The line-frequency transformer place is different, it can be between AC sub-MG and DC sub-MG or between PCC and the hybrid MG; depending on its place, it provides different isolation levels. Also, hybrid MGs with two DC-link voltage levels are equipped with DC/DC VSCs that are a simple buck-boost type or interleaved buck-boost in most cases.

In practice, in TABLE 1, [60] addresses a commercial building in Griffith University, Australia. The implemented topology in that study includes a line-frequency transformer to change the 11 kV at PCC to 0.4 kV for the AC-link, whereas AC/DC VSC connects the AC-link to the DC-link.

Since DSs contribute to the power balance, energy buffer, and fault ride-through, [61] and [62] consider a separate DS-link for DS sub-MG, as provided in TABLE 1. The main disadvantages of this topology are an increase in the complexity of power management, plug, and play capability, and the required control system. In TABLE 1, [66] presents an interface topology with a complex structure; however, MMC implementations and complicated structures are not popular among researchers since they need a complex control and modulation scheme. Standardization of hybrid MG's BIC topologies can simplify the analysis, evaluation, application, and categorization of their control structure.

Although in some studies, the DC-link voltage is decided based on the nominal voltage of the power electronics switches [51], the different levels of DC sub-MG voltages in TABLE 1 are noticeable. DC-link voltage is varied from 48 to 3500 V, which shows the lack of standard DC-link voltage. Based on the limitation of the power-electronics device, power scale, and applications (residential, industrial, electric vehicle charging station), this standardization can unify future researches to some limited, standard DC-link voltage levels and help to reach some standard hybrid MG BIC topologies and hybrid MG structures as well. Different hybrid MG configurations are another research trend, in which different AC and DC sub-MGs are connected to a common link. This link can be DC or AC. In this way, it is possible to connect AC sub-MGs with different voltage magnitudes and frequency levels. The focus of this work is on the regular hybrid MG shown in Fig. 3, which depicts the power-electronic interface schemes of TABLE 1 regarding different connections among PCC, AC-link, DC-link, and DS-link. In this work, the topologies are classified according to their main elements: SST as a high-frequency transformer, DC/DC, or AC/DC BICs, as their configurations in a common hybrid MG shown in Fig. 3.

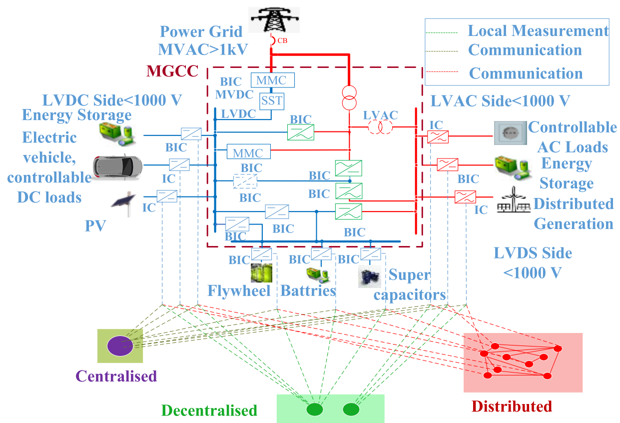


FIGURE 3. Conventional hybrid MG configuration and different possible coordinated control structures.

III. CONTROL STRUCTURES

The control structure of the hybrid MG can be independent of any communication network called communication-less-based. Also, it can be equipped with a communication network, a so-called communication-based control structure. In communication-based control structures, all converters are connected through the communication network. Centralized, master-slave, distributed control methods are communication-based [81].

Regarding the control aspect, the hybrid MG is controlled through different technical issues at different time scales and physical levels.

IEEE p2030.7 [74] categorized all the control objectives into three different control layer functions such that each layer acts in a specified time scale discussed in [11], [75]–[77].

The main task of the hybrid MG management system is to keep the hybrid MG stable, which is located in the primary control layer of control structures [75]. The strategies toward communication-less power-sharing function are dual loop and droop techniques, which will be discussed later.

TABLE 1. Comparison of the proposed categorization of the power electronics interface structures.

Power Electronics Interface Structure	Merits and Limitations								AC Voltages(V)		DC Voltages(V)		Ref.
	Isolation between sub-grids	Utility connection	Possibility of power measurement	Fault isolation	Islanding control	Grounding system possibility	Avoid overcurrent	Needs bulky DC-link inductance	PCC	AC Sub-MG	2nd. level	1st. Level	
Back-to-back CSC	No	By DC-link	Separable for DC and AC sub-MGs	Yes	Possible at PCC	No	Yes	Yes	208	208	-	-	[41]
									-	-	-	-	[42]
Full-bridge VSC	No	By AC-link	For DC sub-MGs	Partially for DC sub-MG	No	Partially	No	No	-	380	-	750	[43]
									-	170	-	280	[44]
									220√2	220√2	-	700	[45]
									220	220	-	380	[46]
									-	-	-	800	[47]
									-	400	-	360	[48]
									-	690	-	2500	[49]
									-	260	-	570	[50]
									-	255-270	-	600	[51]
									-	200	-	400	[52]
Full-bridge VSC + power transformer between AC and DC sub-MG	AC and DC sub-MG	By AC-link	For DC sub-MGs	Partially for DC sub-MG	No	Partially	No	No	208 P	208 P	-	300	[53]
									380	380	-	700	[54]
									220	270	-	750	[55]
									415	415	-	48 V	[56]
Full-bridge VSC + power transformer between the main grid and the hybrid MG	Utility and the hybrid	By AC-link	For the DC sub-MG	Partially for DC sub-MG	No	Partially	No	No	110	110	-	400	[57]
									25 k	690	-	1200	[58] [59]
									11 k	400	-	650	[60]
An AC/DC VSC + DC/DC Converter: AC-link+ DC-link + DS-link	No	By AC-link	For the DC	Partially for DC and DS sub-MGs	No	Partially	No	No	-	230√2 P	-	380	[61]
									-	310, 90	300,200,700	380, 300	[62]
Back-to-back VSCs with their line-frequency transformer	Yes	By DC-link	Separable for DC and AC	Yes	Possible at PCC	Yes	No	No	11 k	3500	-	3500	[63]
2 back-to-back VSCs + transformer between the main grid and hybrid MG	Utility and the hybrid MG	By DC-link	Separable for DC and AC	Yes	Possible at PCC	Yes	No	No	10 k	380	-	600	[64]
2 Back-to-back AC/DC VSCs + autotransformer between main grid and the hybrid MG + An N phase interleaved DC/DC VSC	Utility and the hybrid MG	By DC-link	Separable for DC and AC sub-MGs	Yes	Possible at PCC	Yes	No	No	220	220	-	-	[15]
									-	-	450	200	[65]
									-	-	980	450	[37]
Modular Multi-level Converter (MMC) between 10 kV and high voltage DC-link, SST to LV DC-link + VSC for AC sub-MG	High voltage and the low one	By DC-link	Separable for DC and AC	Yes	Possible at PCC	Not clear	No	No	10 k	380	-	700	[66]
2 back-to-back MMC AC/DC VSCs both connected to the grid	Utility and the hybrid MG	By DC-link	Separable for DC	Partially for DC sub-MG	Partially for DC sub-MG	Not clear	No	No	10 k	-	20 k	-	[16]

The communication-based power-sharing techniques contain droop in a centralized, master-slave, or distributed control structure [75]. However, to increase the reliability of the hybrid MG, a decentralized or autonomous control structure is suggested for use in the first (primary) control layer that is independent of the communication system [75], [78], [79].

The main function of the secondary layer is to recover the frequency and voltage deviation of the local control [77]. Since it is supposed to connect to the grid at this control level, synchronization, power quality, and other functions requiring grid-connection are listed in these control level tasks [75], [77]. However, this and the third layer operate slower; so, they require a slower communication network with low bandwidth for control coordination.

The tertiary control layer, also called the grid-interactive control [76], has the slowest pace compared to two other control levels and it is normally located out of MG like in the Supervisory Control and Data Acquisition (SCADA) system or upper control centers. The main function of this layer is to manage the power among different hybrid MGs' BICs based on the optimization calculations, energy cost, weather forecast; so, this control level is just interconnected to the grid-tied operation mode of the interface structures [12], [77].

Coordinated control plays an important role in smoothing the power transfer between ICs and maintaining stability under different load-supply balance conditions [12], as well as different operation modes [80]. The coordinated control method is a common solution to address frequency issues, particularly, in the islanded-mode of MG operation [81]. To increase the integration of renewable energy sources and different loads in the hybrid AC/DC MGs, multiple sub-MG topologies are attracting more interest. The downside of multiple sub-MG topologies is the complexity of control. Therefore, the coordinated control structure is necessary to overcome the challenge of maintaining stability among interacting sub-MGs [82].

Coordinated control is also necessary for the cluster of MGs to ensure optimal power exchanges among them [83]. Coordinated control structures are classified into centralized, decentralized, and distributed architecture. This classification depends on the data and information exchange between the controlled entities [5], [75].

A. CENTRALIZED

This structure naturally consists of a central controller and concentrates information in this node [84]. The central controller decides actions based on the control objectives and the information available from both AC and DC sub-MGs of the hybrid MG. A centralized structure is easy but expensive to implement.

B. DECENTRALIZED

The main characteristic of this structure is that it needs no communication links. The decentralized control methods require only local measurements [85]; therefore, it provides the ride through communication malfunction capability and enhanced system reliability [62]. However, the drawback of the decentralized control structure is in the practical utilization: low accuracy of power-sharing and sensitivity to line impedance, poor performance in nonlinear load sharing, inherent load-dependent frequency, and amplitude deviations. Moreover, the effectiveness of this control structure is questionable under the circumstances that the power exchange between two sub-grids is required. There is a trend in recent research to develop tuning methodologies to adjust the droop characteristics to overcome the issues regarding nonlinear load sharing in a decentralized control structure [86].

C. DISTRIBUTED

This structure consists of independent advanced controllers, which are connected and therefore are aware of the mutual situation. A distributed control structure is particularly efficient for the multiple sub-grid topologies [94]. This structure enables some level of cooperation between different control entities, but the main issue is how to share data and define the access level of information. Meanwhile, distributed control is an emerging concept to enable the plug-and-play feature and handle topological variations through its scalable nature. Fig. 3 illustrates these three control structures for a hybrid AC/DC MG. TABLE 2. presents a comparison of the coordinated control structures of the hybrid AC/DC microgrid.

IV. CONTROL STRATEGIES

Some control objectives in the hybrid MG studied so far are power management, synchronization, parallel BIC operation, stability improvement, voltage, and current control, energy storage coordination, islanding detection, seamless transition between BIC operation modes, economic energy dispatch, black start management, fault detection, unbalanced voltage control, power quality, and harmonics mitigation. These control objectives can be divided into energy management and protection issues based on their related fields [9], [75], [120]. Different control strategies are implemented to control these objectives. Common strategies in BIC control will be discussed in this part.

A. POWER-SHARING

The power-sharing objective is possible by making a balance between production and consumption; in this way, voltage and frequency stability are also achieved. So, the power-sharing objective overlaps the stability issue, which will be discussed below. Power-sharing strategies are classified into three major concepts: current or voltage control, droop, and Virtual Synchronous Generator (VSG). The current or voltage control is the basic concept implemented in the droop and VSG concept as well. The droop technique concentrates on different ways of power-sharing among multiple BICs and ICs. The VSG concept is applied to enhance both the steady-state and transient stability of droop power-sharing [79].

TABLE 2. Comparison of coordinated control structures.

Structures	Disadvantages	Advantages	Applications	References
Centralized	Expensive and complex Difficult in expendability Decreased redundancy, reliability, and flexibility	Standardized procedures Easy implementations More accurate power-sharing Better power quality Faster transient response Less circulating current among ICs The optimal decision is guaranteed	Secondary and tertiary control Optimization functions and Economic dispatch Standalone MG	[84], [87], [88], [89], [90], [75], [91], [92], [93], [94] [93], [95], [96]
Decentralized	The optimal decision is not guaranteed Less accurate in power management Slow in transient response Deviation in voltage and frequency control Poor power quality control More current circulation	Does not need communication Enables hierarchical control Least computational burden More reliable Less expensive and expandable Redundant, Flexible, and modular	Primary (Droop) control	[97], [98], [85], [99], [82], [86], [100], [94], [93], [95], [96]
Distributed	Insecurity in sharing information Signal Transmission delays Difficult in expendability Decreased reliability, redundancy, and flexibility	The optimal decision is possible Accurate voltage and frequency control More accurate power-sharing Better power quality and transient response Less circulating current among ICs	Secondary and tertiary control	[101], [62], [102], [103], [75], [91], [92], [93], [94]

The traditional Proportional Integral Derivative (PID)+ Resonance (R) controller, Model Predictive Control (MPC), Fuzzy, adaptive fuzzy, neuro-fuzzy Logic Control (FLC), and Reinforcement Learning (RL) are the most popular control techniques in these three power-sharing strategies. MPC is the most popular alternative for PID+R methods. MPC in DG and ES application is studied in [121]–[126].

[121] provides a review of model predictive current control with the SVM modulation technique for the DGs. [122] uses MPC for PV applications. In this work, model predictive current control and model predictive voltage control are used for MPPT and DC droop control respectively.

One of the main issues in the MPC is the determination of the cost function [126]. Cost functions contain control objectives or target sets and the limitation sets [106]. [126] and [127] categorize cost functions based on the control objectives and applications successively. The MPC can be adopted to optimize the switching function, which is called the Finite Control Set (FCS) MPC [107]. However, it may result in variable switching frequency, spreading the frequency spectrum and higher THD, so some modifications in the cost function are necessary [111], [118]. MPC with an external switching module works with the fixed switching frequency called Continuous Control Set (CCS) MPC [119]. The input of the cost function is an error signal that must be minimized. This error signal is the difference between the reference value and its future predicted value. The MPC methods implement the state-space model of the system to predict the future states and calculate the optimal control. As these methods utilize updated states in each sampling time, they are equipped with online optimization inherently [111]. On the other hand, generalized predictive control employs the system transfer function utilized in offline optimization [111].

The general MPC application in hybrid MGs summarized in TABLE 3. will be discussed in this part and other parts of the paper.

RL is a heuristic intelligent technique consisting of environment, agent, action, rewards, penalties, and states [128]. RL aims to learn how to maximize the rewards for the agent based on the rewards or penalties of its actions in predefined environment states [129]. Different studies implement RL to optimize the schedule of DGs or DSs based on their predicted product, energy price, and load demand [128]–[133].

FLC is another intelligent control technique which emulates human decision making [134]. FLC is used in the control of DSs and DGs to provide reference values [135]–[143] or tune the optimized parameters of PID+R regulators [144] in different studies. In summary, the popular FLC method is Mamdani with 3 to 7 triangular or trapezoidal membership functions.

The pros and cons of different control techniques are summarized in TABLE 4.

These three main concepts of power-sharing and their control techniques are discussed below.

1) VOLTAGE AND CURRENT CONTROL CONCEPT

Many studies have focused on this control objective, regarding IC and BIC control. Each IC in the MG has the grid-tied or the islanded operation mode. In the grid-tied mode, the ICs follow the main grid voltage; so in the control strategy, a current-controlled grid is followed. In the islanded mode, the priority is to provide a stable voltage, so the grid-forming strategy is applied. This strategy is voltage controlled. In this section, different strategies toward this concept will be discussed.

a: PID+R TECHNIQUE (DUAL LOOP)

In the grid-tied and islanded mode, apart from the synchronization method, the same procedure is applied in many papers using traditional dual loop PID+R controllers. A reference current or voltage value is tracked by an outer voltage loop and inner current loop in abc (natural frame), dq (synchronous reference frame), or $\alpha\beta$ (stationary reference frame)

TABLE 3. Proposed categorizations of MPC studies based on their applications in hybrid MGs BICs.

MPC Application	Control Objective in the Cost Function	Ref.
AC/DC VSC Control	Current, Voltage, Power	[58], [104], [105]
	Current, Voltage, Power, Switching function	[106], [107],[105], [108]
Coordinated Control in a Hybrid MG	Power balance in both grid-tied and islanded modes	[58], [109]
	Power balance in both grid-tied and islanded modes, Switching function	[59] [110]
Stability Analysis	LCL filter variations on system stability	[111]
Droop Control	Current, Voltage, Power	[109], [112], [113]
Virtual Synchronous Generator	Frequency, Voltage, Power	[114]–[117]
Power Quality	Current, Voltage	[118], [119]

TABLE 4. Comparison of different power-sharing control techniques.

Techniques	Pros	Cons	Ref.
PID+R	Less computational time Fixed switching frequency Easy to implement	Dependency on the mathematical analysis Dependency on the dynamics of the system Complicated control system in terms of the cascaded control structure, feedback loops, and PWM structure Time-consuming parameter tuning of PID+R Slow in the dynamic response	[123], [124] [128] [130] [145]
MPC	Multi-objective optimization control technique Fast transient response Simplifies the control structure by combining the modulator block	More computational burden Needs high sampling frequency FCS produces extra harmonics Difficulty and uncertainty in the determination of weighting factors in the cost function Dependent on the accuracy model of the system	[105], [106], [107], [106], [107], [111], [118], [119], [121]–[126]
RL	Able to learn without pre-required knowledge Able to combine with other techniques	Convergence dependency on the initialization	[128]–[133], [146]
FLC	Does not need an accurate mathematical model of the system Does not need an accurate model of training Easy technique for control of complicated systems Simple rule-based membership functions Less sensitivity to disturbances Able to combine with PID+R controllers	Time-consuming in setting the membership functions Not optimized in terms of identifying membership functions Complicated in increasing numbers of inputs and outputs	[128] [147], [135]–[144]

frame in the single or three-phase and the s or z domain [9], [148]–[161].

In [158] and [154], despite showing simulation results in various operation conditions, the experimental results are limited to the voltage output and THD. Studies in [152] compare the voltage steady-state error in experimental results in four control conditions: PID, PID+ R, PID+R+ load current feedback, and dq frame control with load current feedback in no-load, resistive, capacitive, and first-order nonlinear load. Its experimental results show better performance of PID+R+load current feedback; however, in nonlinear load, especially for higher-order, the effects of the harmonics and EMI are increased. In [153], a limited setup result with harmonics and EMI effects is shown; in other words, it neglects different load types and transition conditions like load change. Digital control is applied in [156]; the results show the suitability of steady-state response but a weak transient response of the proposed control method.

The experiments in all the studies referenced were done on a scale of less than 10 kW. However, the required power scale in MGs is higher. This fact points out the limitation of a power-electronics device in practical application. Consequently, most studies in large power-scale prove their proposed control methods in simulations rather than in the experimental setup. The exception case is [159]. In this study, in the experiment, a power scale of 500 kW was used. A three-level three-phase full-bridge VSC with Gate Turn-Off thyristor (GTO) switches was applied; however, GTO has the limitation of low switching frequency operation. The experiment with the switching frequency of 1620 Hz is utilized, whereas the low switching frequency deteriorates the output power quality.

The current-controlled technique is easy to implement with BICs. It eliminates the circulating current and decouples active and reactive power, which are its positive points but its function is dependent on the voltage supply; as a result, this technique is not suitable for a weak hybrid MG [11]. The voltage-controlled technique is capable of providing a stable voltage, so it is suitable for the islanded mode and a weak hybrid MG [11]. Easily circulating current, coupling active, and reactive power, easily influenced by the line and filter impedances in the droop technique are some of the negative points of this method [11].

b: MPC TECHNIQUE

MPC application in voltage-controlled and current-controlled concepts can be divided into FCS MPC, hybrid FCS MPC, CCS MPC, and hybrid CCS MPC. Hybrid types contain an outer PID+R loop in their control blocks, as shown in TABLE 5. [105]. TABLE 5. categorizes the references based on this division and compares them. The measuring values can be transformed to the reference power in the control block.

Reference [106] confirms that the steady-state and dynamic response and THD control of FCS MPC are better as compared to the hybrid FCS MPC; however, the hybrid FCS MPC technique is more robust against parameter variations. On the other hand, [162] shows that the performance of the hybrid FCS MPC is better than that of FCS MPC regarding the LCL resonance frequency, stability, and sensitivity enhancement.

References [58], [59], [110] address the application of MPC in both the grid-tied and the isolated mode of the hybrid MG. The experiment in [58] is conducted in the hardware-in-the-loop in which case the the performance of CCS MPC is better than that of a hybrid type in terms of THD and transition states. In a similar hybrid MG, [59] suggests implementing model predictive power control and model predictive voltage control for the DS converter and AC/DC BIC respectively. The ES converter acts as a master in the islanded mode. Its cost function is designed to minimize the DC-link voltage ripple and balance the DC-link current in the islanded and the grid-tied mode successively, considering SOC and DS current constraints. The connection or disconnection of the load side capacitor generates a spike current, which is not solved in this work. Also, the reference reactive power is assumed to be zero, which limits the AC/DC BIC application in ancillary service to the utility. Optimization of the ES lifetime is not addressed in [59], [110].

Prediction horizon is an important issue in MPC. Increasing the prediction horizons improves the system performance and its stability [127], but it leads to an increased computational burden [127]. Most studies use one horizon step [58], [104], [106], [107]. However, to compensate for the processing time delay of digital hardware, two horizon steps are widely accepted [162].

c: RL TECHNIQUE

RL technique is used in [146]. This study proposes the RL-based fuzzy PID to control the frequency in an MG. The MG consists of different RESs and ESs. The Fuzzy-PID is utilized to prepare flexible parameters. Seven trapezoidal membership functions are regraded for three parameters of PID, which are selected based on genetic algorithm optimization. RL defines the reward action in each interval. Comparison of the results of the RL-based fuzzy-PID with the fuzzy-PID and the classic PID shows that the transient response of the proposed technique is better in load change conditions. Less settling time and decline in undershoot are the merits of this technique; however, it has more overshoot.

d: FLC TECHNIQUE

FLC in the voltage-controlled concept is used in [163]. It implements and simulates FLC for the self-tuning of PI regulators for a VSC IC in the dq frame. The results confirm the flexibility of the FLC controller compared to classic PI regulators in load change conditions. FLC utilization in the current-controlled VSC is studied and simulated in [125], in which FLC provides a referenced component current in the AC side. DC-link error voltage and its derivative are the inputs of the FLC regulator.

2) DROOP CONTROL CONCEPT

Droop-based control is the most common control technique, which can be implemented in communication-less-based networks as well as in communication-based networks. As the AC/DC BIC VSC transfers the active power between AC sub-MG and DC sub-MG, it implements both AC and DC droops called a hybrid droop. In this section, all these droops are categorized into AC droop, DC droop, hybrid droop, and active droop.

a: AC DROOP

Common AC-droop is based on the dominant inductive or resistive characteristics of the line and filters [164], so it includes active power-frequency P-f and reactive power-voltage Q-V characteristic for inductive characteristics and P-V, Q-f for resistive type [165]. Studies in [166]–[168] focus on the AC droop based primary control using PID+R controllers in an islanded MG, in which different AC droop types of static and dynamic, voltage regulation improvement, dynamic voltage regulation improvement, and virtual frame are explained. Also, different control block diagrams regarding communication-based techniques, such as centralized, distributed, master-slave, and angle droop, are explained in [166], [169].

In terms of MPC application, [112] uses hybrid FCS MPC for AC-droop control of parallel VSCs. Virtual resistive and droop loop provide the reference voltage for the FCS MPC block. [109] implements AC-droop-based CCS MPC for the primary and secondary control level of AC/DC VSCs in an islanded hybrid MG. The primary level of MPC has a steady-state error in the output voltage frequency and magnitude, which is compensated by the secondary level MPC.

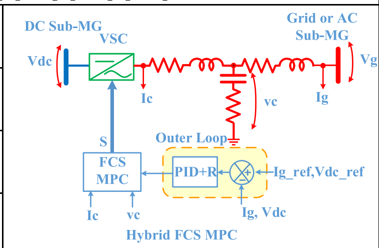
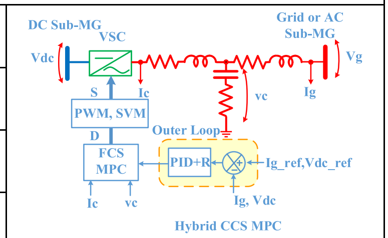
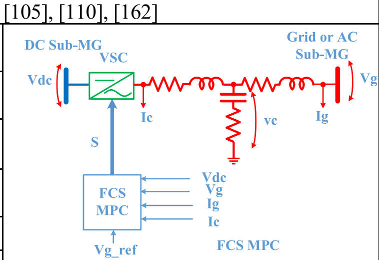
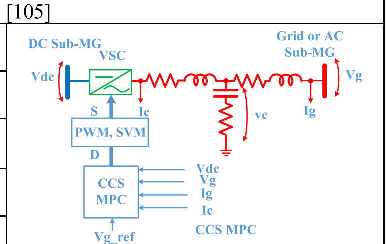
The study in [94] presents three different control levels of the islanded ACMG, focusing on power-sharing and power quality in load changes. This work proposed droop control for the first control level, which could reach the voltage and frequency in an acceptable limit but it was not successful to keep them at nominal values. So the multi-stage based $H\infty$ controller as the second control level was introduced, which was able to reach those values to their nominal amounts. This control technique improved power quality as well. To enhance the performance of the second layer, the HS optimization algorithm for weighting parameters of $H\infty$ was implemented.

b: DC DROOP

DC-droop is based on the DC voltage and power. Generally, AC voltage droop solutions are expandable to the DC-droop as well [78]. DC droop is applied in ESs and DGs, which are discussed in [51], [61], [62], [170]–[174].

FLC utilization for adaptive DC-droop control in DGs and DSs is studied in [175]–[177]. FLC inputs are DC-link error voltage and SOC of ESs. The FLC output is the adaptive resistance of the DC-droop. Results of hardware-in-the-loop show that the performance of FLC in the power-sharing and

TABLE 5. Comparison of MPC applications in VSC current-controlled and voltage-controlled techniques.

		Block Diagram representative of control technique			
	Type	Hybrid FCS MPC		Hybrid CCS MPC	
	Ref	[106], [107], [105], [110], [162]		[58], [105]	
Control Loop Features and Performance	Control Loop Numbers	2		2	
	Computational Effort	Low		High	
	Modulator Stage	Not Needed		PWM or SVM	
	THD	Moderate		Moderate	
	Steady-State Response	Good		Good	
	Dynamic Response	Good		Good	
	Type	FCS MPC		CCS MPC	
	Ref	[59], [106], [105], [110], [162]		[58], [104], [105]	
Control Loop Features and Performance	Control Loop Numbers	1		1	
	Computational Effort	Moderate		High	
	Modulator Stage	Not Needed		PWM or SVM	
	THD	Moderate		Low	
	Steady-State Response	Good		Good	
	Dynamic Response	Good		Good	

equalizing SOCs among DSs is better in different conditions. Despite the DC-link voltage spike in the transition condition from the constant voltage-controlled mode to the droop mode of DSs, FLC has no steady-state error in the DC-link voltage compared to the fixed DC-droop.

c: HYBRID DROOP

Hybrid-droop is utilized in BIC power-sharing control, which links the AC droop in the AC side to the DC-droop on the DC side. The coordination of these two droops P-f and P-V is used in the BIC control for proportional power-sharing of AC sub-MG and DC sub-MG respectively [178], [179]. As shown in Fig. 4, to make the AC frequency and the DC voltage comparable, normalized or per unit (p.u.) amount of them is used in the hybrid droop. It is described and compared in TABLE 6. [11], [14], [78], [97], [180].

Besides the normalized hybrid droop discussed earlier, [179] and [97] introduce a modified hybrid droop and voltage-current droop control for the power-sharing strategy in AC/DC BIC as well. The modified droop is based on the direct relationship between the AC frequency and the DC voltage. In this equation in TABLE 6., C_{DC} and T_S are DC common bus capacitors and switching periods respectively.

FLC application in the hybrid-droop control is studied and simulated in [181]. The FLC controller inputs are per-unit frequency change and the DC-link voltage per-unit change, whereas the output is the reference active power. The simulation results show that the proposed method has a suitable performance, but membership functions are not clarified in this study.

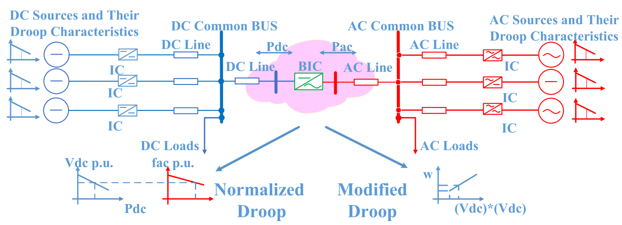


FIGURE 4. Hybrid Droop Scheme of BIC in a conventional hybrid MG.

Hybrid droop is not accurate enough in power-sharing. One practical problem of hybrid droop is measuring the frequency deviation. Equipment accuracy in the frequency deviation sensing is not sufficient for accurate power-sharing [50]. So, a voltage-controlled method that implements virtual impedance is proposed. In that method, the droop characteristic is achieved by measuring the AC side active power and the DC side voltage. The simulation results confirm the suitable steady-state response; however, noticeable oscillation in the DC voltage transient response needs to be declined.

Another way to enhance the accuracy of power-sharing is the high droop slops of P-f and P-V, which results in instability, especially in weak MGs. As a result, adding an extra loop to modify d component of the reference voltage is suggested and simulated in [169].

The other problem in accurate power-sharing is related to the voltage. Although the frequency is a global variable, the voltage is not. In other words, as shown in Fig. 4, line resistance and impedance in DC and AC sub-MG between DGs and the common AC or DC-link in the hybrid MGs provide voltage drops. These voltage drops are not considered

TABLE 6. Comparison of different hybrid droop types in AC/DC BIC.

Droop type	Equation	Advantages	Disadvantages	Ref.
Normalized	$F_{p.u.} = \frac{F - 0.5(F_{Max} + F_{Min})}{0.5(F_{Max} - F_{Min})}$ $V_{DC\ p.u.} = \frac{V_{DC} - 0.5(V_{DC\ Max} + V_{DC\ Min})}{0.5(V_{DC\ Max} - V_{DC\ Min})}$	Easy to implement with one PI Good active power-sharing	Accuracy depending on the measuring device Increased loss in load change (continuous working)	[179] [14] [180] [50] [181]
	$F_{p.u.} = \frac{(F - F_{Max})}{(F_{Max} - F_{Min})}$ $V_{DC\ p.u.} = \frac{(V_{DC} - V_{DC\ Max})}{(V_{DC\ Max} - V_{DC\ Min})}$	Easy to implement with one PI Good active power-sharing Considering threshold zones to avoid overload or underload condition	Accuracy depending on the measuring device Line impedances are needed in [178] Inrush DC current in load change in [78]	[78] [178]
Modified	$w_0 - w = (\frac{m_x \times C_{DC}}{2 \times T_s})(V_O - V_{DC})(V_O + V_{DC})$	Decoupled P and Q sharing Reduced mode transition loss Good active power-sharing	Accuracy depending on the measuring device More complex and costly	[179] [97]
Voltage-current	-	Better power-sharing functionality Required low bandwidth communication network	PR tuning difficulty Coordination tuning of two PRs Different control in rectifier or inverter mode	[179]

in the power-sharing control method; so, at imbalanced load or imbalanced line impedance conditions, it causes inaccuracy in power-sharing [178]. Moreover, increasing DGs power demand can result in shifting the system to an unstable zone [167]. Consequently, poor stability margin is another negative point of the communication-less droop technique addressed in many studies. Considering voltage drop [178], virtual impedance [165], [171], [182], [183], virtual P and Q frame control [184], communication-based control [185], and secondary control level [186] are the main solutions. In [173] and [174], the line and filter voltage drop is compensated by adding the voltage error signal to the reference voltage of droop [187] implements the same concept in the current-controlled mode.

In the virtual impedance method, by adding the virtual impedance in the control loop, the dominant impedance is controlled to be inductive [184], [188], or resistive [189]. The quantity of this virtual impedance is known [183]. As a result, the line and filter impedances are small enough to be dominated by the virtual impedance on the droop deviation voltage [185]. In the predominantly resistive output, the nonlinear power-sharing can be facilitated [183], [189]. It improves the overall system damping, current harmonic sharing among parallel ICs, and power-sharing in imbalanced loads or line impedances. References [190] and [174] add a virtual impedance by a feedforward loop to the P-V droop. References [171] and [172] propose a control system to minimize the circulating power. First, their experimental results reveal the effects of EMI. In [183], two single-phase full-bridge inverters are applied as the experiment setup. The implementation of a 7.5 kHz switching frequency has also resulted in the low power quality of the output voltage.

To minimize the circulating power between the AC and DC side of BIC and overstressed on DGs, e.g., some studies [78] proposed to apply boundaries in droop characteristics. These limitations are applied to overfrequency and under- frequency in AC and overvoltage and undervoltage in DC droops to force BIC to work in a fixed power mode, e.g., when the frequency in the AC part of BIC reaches its minimum amount, the BIC continues working as fixed power.

Harmonic-sharing is another issue that should be satisfied based on the load demand discussed in [165].

The hybrid droop in the case of multiple AC/DC BICs is modified based on the error-signal droop, which gives more accurate results [180]. Error-signal droop is the difference between normalized frequency and normalized DC voltage. In this method, BICs provide the reference power for both AC and DC sub-MG with the current-controlled mode explained in detail in [180]. Theoretically, considering the analog-digital conversion and sampling requirement, the voltage and frequency deviation boundaries of 2% and 5% are recommended but in practice, a slightly wider range (5% or higher for both) is possible [50], [180]. As the main grid link acts as a slack link, the droop control in the grid-tied operation is not that much crucial as in the islanded mode, regarding the power balance and stability issues [180].

Coordinated autonomous power management in a small hybrid MG consisting of back-to-back AC/DC VSCs as BIC with DC DSs is studied in [63]. AC/DC VSC connected to the PCC of the main grid works as a current-controlled mode to stabilize the DC-link voltage through tracking reference current angle in the main grid side. Another DC/AC VSC that connects the DC-link to the AC sub-MG works in a droop to transfer extra power to the AC or DC side. DC DSs work in constant power or droop [62] also studies primary level hybrid droop for similar MG with AC/DC and DC/DC VSCs. The process of general AC droop, general DC droop, and hybrid droop is explained. Besides, DS droop works based on the global supply-demand of the hybrid droop. The general DS droop based on the SOC condition of DSs in charging and discharging mode is discussed. To prevent unnecessary power circulation, and frequent charging/discharging of the DSs, the multilevel primary control is proposed. In this method, three different zones are introduced. The lower level is AC-droop-based ICs or DC-droop-based ICs that work separately in AC sub-MG or DC sub MG. The second level consists of hybrid-droop based AC/DC BIC in which AC and DC sub-MG transfer power to stabilize the AC frequency and the DC voltage. The higher level is DC-droop-based DS BIC, in which the global extra or deficit power is transferred to the DSs. All these zones are determined by the normalized frequency and DC voltage. In the end, to avoid retrigger DSs in the transition mode, modifications in boundary zones are added.

Although the focus of this paper is on the conventional hybrid MG, as shown in Fig. 4, the complex configuration of the hybrid MG is also addressed in some papers. These complex hybrid MGs contain different configurations of AC and DC sub-MGs with AC or DC common bus. In this regard, [99] studies a decentralized coordinated power-sharing strategy in a hybrid MG with DC common bus, including multiple AC sub-MGs and DC sub-MGs that are connected by the DC common bus. DC common bus voltage is regulated by the DSs that are separated into a specific sub-MG. A new P-V_{DC}^2 DC droop characteristic is proposed for power-sharing among DSs in the main DC bus, whereas normalized hybrid droop is used in the AC/DC VSCs power-sharing strategy and a normalized V_{DC} droop characteristic is implemented in DC/DC VSCs in the DC sub-MGs. A coordinated power-sharing strategy is suggested based on the DC common bus voltage, AC sub-MGs frequencies, and DC sub-MGs voltages.

d: ACTIVE DROOP

Slow transient response, voltage deviations, the dependency of the DC droop on the output resistance, and the trade-off between power-sharing, frequency, and voltage deviations are the drawbacks of the communication-less-based droop [165]. Communication-based droop control is also called active droop. Active droop can be implemented in centralized, master-slave, average load sharing, and circular chain control [64], [75], [179], [191], [192]. In a centralized strategy based on every ICs droop characteristics, their reference currents or powers are transferred to them [165], [191]. In the master-slave, the master IC regulates the voltage, working as voltage-controlled, whereas other ICs work as slaves in the current-controlled mode [93], [165].

Master IC acts as a centralized controller, sending each ICs reference currents [165]. Considering the master IC role, three control schemes exist: 1- Dedicated master IC: the master IC is fixed; 2- Rotary: the master IC is arbitrarily selected; 3- High-crest current: the master IC is selected based on the maximized power supply ability among ICs [165]. Average load sharing is based on dividing the load among ICs [64]. The circular chain control concept is based on the AC power ring in the distribution power line; in this method, the study in the communication ring network is used among ICs [191], [192]. In this scheme, any IC can act as master IC controlling the voltage, whereas other ICs work as slaves in the current-controlled mode, tracking their previous reference current IC [191], [192].

Reference [185] employs an adaptive virtual impedance to get the Q reference value through the communication system on a 2 kVA prototype consisting of two ethernet-equipped VSCs. The experiment in this study confirms the suitable functionality of the proposed method in equally reactive sharing during the step load change in an unequal line impedance condition. However, the test is limited to the two DGs with the same characteristics and the same ICs.

Primary control deviations are compensated through secondary level control. This control level is mainly equipped with a communication network. Reference [61] proposes the primary and secondary control level for a hybrid MG with AC/DC VSC and DC/DC DS VSC. After eliminating the deviation between the normalized frequency and the DC voltage by the secondary control in AC/DC VSC, it will be difficult for primary control to detect the frequency and the DC voltage deviation to determine the required power and its direction. Consequently, a virtual deviation and a normalization definition are introduced as the contribution of this work. This virtual deviation indicates the potential deviation, which is caused by the primary control. As a result, the primary hybrid droop can cooperate properly with the secondary control based on the simulation and hardware in the loop results.

Reference [43] improves the transient response in the transition mode with a shorter transient time and less transient peak in a hybrid MG, with the proposed interface topology of dual parallel AC/DC full-bridge VSCs between a slack DS-link and the PCC or AC-link. One BIC works in the current-controlled-mode, whereas the other works as the voltage-controlled-mode. In the grid-tied operation, converter 1 works as master, whereas in the islanded operation, converter 2 works as master. Dual parallel BICs provide seamless transition from grid-tied (current-controlled-mode) to islanded (voltage-controlled-mode) or vice versa. This study proposes an adaptive virtual impedance-based coordinated control structure for the voltage-controlled VSC in the $\alpha\beta$ frame in the grid-tied mode. To mitigate the harmonics and imbalanced voltage disturbances at PCC, the virtual impedance voltage drop is composed of three different components: positive sequence, negative sequence, and harmonic components. Since converter 1 works in the current-controlled mode, it rejects load harmonics; consequently, converter 2 has to provide the required harmonics, resulting in variation in the PCC voltage. As a result, converter 2 defines the reference current for converter 1 based on the power demand and mitigation of harmonics and imbalanced voltage disturbances in the islanded operation.

A coordinated droop control method for two back-to-back SST VSCs combined with a DS in a medium voltage hybrid distribution system studied in [16] is also applicable for a hybrid MG requiring high reliability. Reference [16] extracts the equivalent circuit model of the MMC based on [193]. In this study, the DS control is divided into constant power control in normal conditions and the voltage control mode in an abnormal condition. In other words, DS is implemented not only in smoothing the DGs output variations but also to provide slack DC-link voltage in abnormal operation to enhance the system stability. However, the efficient operating condition of DS and SOC are not considered in this study.

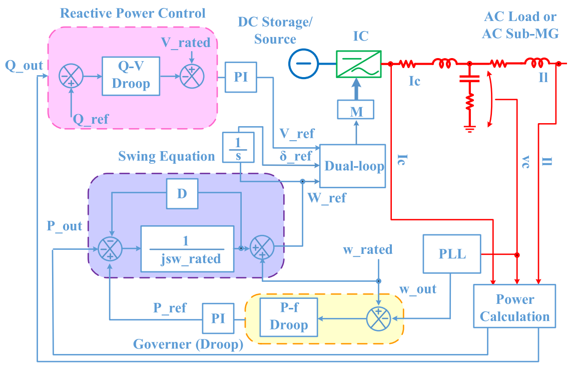


FIGURE 5. General VSG Control Diagram.

3) VIRTUAL SYNCHRONOUS GENERATOR (VSG)

Increasing penetration of the non-inertial DGs in the hybrid MG makes it vulnerable to frequency instability due to the drop in the rotating-physical-mass-sources inertia [194]. This can lead to a severe Rate Of Change Of Frequency (ROCOF). Then ROCOF relays operate against the islanding condition, and finally cascade effect of disconnecting DGs can happen [194]. To increase the DGs inertia for the enhancement of the hybrid MG stability, Distributed Storage (DS) in parallel with DG is proposed in [195]–[199], called Virtual Synchronous Generator (VSG). In some studies, it is also called Synchronverter, which refers to the VSC control [195], [200]. VSG emulates synchronous generator behavior through the swing equation, as shown in Fig. 5. The total procedure of simulating between the synchronous generator and VSG is defined in [195]. In [200], the transient condition of [195] is improved.

VSG (with or without droop) provides the required P or angle, whereas droop provides the required Q or voltage magnitude. To enhance the control system performance [196], [197] adopted inertia, [198], [201], [202] VSG with droop control techniques, in [46], [79], virtual inductance stator adjuster is proposed.

MPC applications using the VSG concept are investigated in [114]–[117], whereas [203] studies FLC utilization in VSG control.

All the studies mentioned focus on the VSG control of DG's or DS's ICs, whereas [56] brings the VSG concept into the BIC application in a hybrid MG. The aim is to reduce the required ultracapacitor size. This can be done by increasing the hybrid MG's inertia by employing a suitable control technique for the available synchronous generator and BIC as the DS in the AC side during the power disturbances. The combination of a synchronous generator and BIC as the short-term DS with the VSG technique is proposed to enhance the transient performance of the hybrid MG through controlling the BIC's output frequency. This study applies the islanded mode with power disturbances inputs, in which the hybrid MG is more fragile. The impedance line that generates deviation in the voltage in the synchronous generator and BIC is also considered. The results confirm a noticeable decrease in the variations of BIC active power in the transient condition, leading to a decline in the ultracapacitor power variations, which results in the lower required short-term DSs capacity like ultra-capacitors.

B. POWER QUALITY AND HARMONICS CONTROL

There are so many factors that deteriorate the power quality in the MG, e.g., voltage unbalance, transient, harmonic distortion, nonlinear loads, DGs, voltage sags, and swells, under-, and overvoltage, voltage notching, fault and outage, flicker and power electronic switches, which are some sources of power quality disturbance [204]–[208]. Bad quality of electrical power results in quick wear-out of the electric equipment, increasing the maintenance expenses, and even failure or shut- down of the system [209].

1) EMI REDUCTION CONTROL

EMI is referred to as radiated interference and conducted interference [210], whereas the latter is the focus of this part. High-frequency EMI is one source of pollution to the main grid that should comply with the Electro-Magnetic Compatibility (EMC) of nearby devices [211], [212].

The IEEE standard 1547 [213] determines the regulation for harmonic injection to the main grid. In this document, the acceptable percentage injection of different harmonic levels is clarified. Regarding EMI noise regulation, different EMC standards for different applications exist, such as the International Special Committee on Radio Interference CISPR32, which clarifies the conducted EMI limitations in the smart grid [266].

EMI is produced by high-switching frequency due to high $\frac{dv}{dt}$ or $\frac{di}{dt}$ at the switch's drain, the Common Mode (CM) current flowing in the phase and neutral wires, and returning through the ground [214], [215]. Differential Mode (DM) current as another source of EMI is mostly generated at normal switching operation flowing between the phase and the neutral [214]. In the hybrid MGs with non-isolated BIC, the low impedance CM path is generated between the grounded DC sub-MG and the grounded AC sub-MG [18]. In this system, AC sub-MG and DC sub-MG are coupled by the BIC and the ground [18].

EMI mitigation solutions can be divided into two main classes: to mitigate at the generation level and to decrease the generated leakage current along paths [214]. Most techniques in the latter apply the general concept of increasing the impedance method to tackle the leakage current [18]. As shown in Fig. 6, designing external or internal filters is a popular method to decline the EMI effects on the end receiver [215]. External filters are outside the noise source circuit, which is the power electronic circuit, whereas internal filters refer to the inside of the printed circuit board. Different types and designing processes and challenges are discussed in [209], [216], [217]. LCL and L types are the most commonly used passive filters in the studies demonstrated in Fig. 2.

At the generation-level solutions, the focus is on the IC's or BIC's switches. As shown in Fig. 6, it includes topologies and switching techniques [214], [211]. Different topologies are possible by different circuit topologies discussed earlier and component specifications [214]. In the switching technique, the solutions are in the modulation control and soft transition techniques [214], [218], [219]. Some studies apply hybrid techniques that refer to the use of multiple solutions [210].

The external passive filter size is reduced by employing the external active filter. It can be applied as a feedforward filter and feedback filter explained in [214]. The stability issue is the main challenging topic in a feedback filter in real conditions with a nonideal component loop [215]. The lower frequency range of EMI is 150 kHz to 5 MHz, which is the dominant zone for disturbance mitigation [215]. This study [215] proposes a CM active feedback filter for off-line IC aiming to mitigate the low-frequency EMI. The CM noise current is measured, and the compensated noise voltage is injected into the power line by a voltage feeding transformer to reduce the EMI, which is a current-sense voltage-feedback active filter. Techniques shown in Fig. 6 can be divided into the power section and the control part. Different power-stage solutions are discussed in [212], [214]. Among the topics represented in Fig. 6, the red color parts as the circuit control of the designed topologies and PWM modulation can be employed through ICs and BICs control.

In the topology and circuit, the focus is on the rearrangement of the layout and circuit and grounding issue, e.g., by reduction of parasitic capacitors of the heat sink by different methods such as grounding [214].

In the PWM technique, it is common to apply the variable switching frequencies to spread the EMI noise spectrum [214]. Random carrier frequency, random PWM, and chaotic frequency modulation are some of the PWM techniques, which improve the EMI effect [214], [210].

2) POWER QUALITY CONTROL

Power quality objective in the AC sub-MG refers to the provision of sine current and voltage as the reference curves, whereas in the context of DC sub-MG, it refers to the reduction in the ripple, sag, and swell in the DC current and voltage [15]. Power factor, unbalance factor, and Total Harmonic Distortion (THD) are three main criteria for evaluating the power quality in the AC context [54], [220]. Based on the IEEE standard 141 [221] and 519 [222], the voltage unbalance factor and THD should be kept lower than 2% and 5% respectively in the utility distribution network [54].

Due to the less inertia of the MG in the islanded mode compared to that of the grid-tied, any changes like nonlinear or unbalanced loads can produce harmonic distortion [204], [205]. In the grid-tied mode, any unbalanced condition in the PCC can change the power quality of the MG.

Filters are the main tools to eliminate the harmonic distortions, which are classified into passive, active, and hybrid filters [206]. Passive filters contain different configurations of inductance, capacitance, and resistance, forming low-pass, high-pass, middle-pass, and middle-no pass filters, the structure, and functions of which are described in [206], [223]. Passive filters are not flexible in load variations; however,

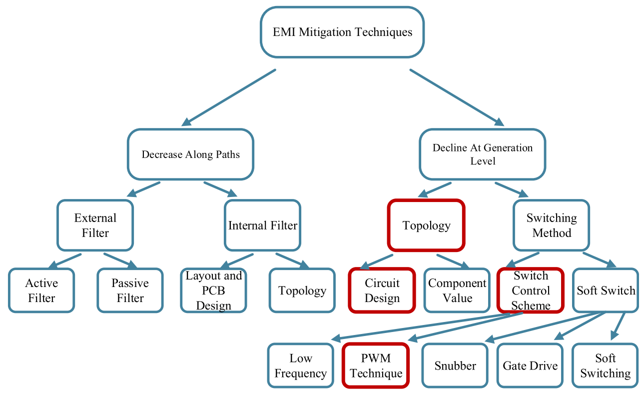


FIGURE 6. Classification of EMI Mitigation Techniques [214].

active filters have the desired dynamic response [206], [224]. Active filters are equipped with switches; in other words, ICs and BICs can work as active filters as well [2], [204]. The most widely used filters are the hybrid type, which leverages both active and passive filters. Different controllers like PI, PR, hysteresis, deadbeat, repetitive, $H\infty$, the fuzzy, and neural-based controller can be applied to improve the power quality, which is discussed and compared in [204].

Reference [153] focuses on PR implementations and their role in the compensation of specific harmonic components. Specific harmonic elimination modulations like harmonic elimination Pulse Width Modulation (PWM) [225], [226] are other ways to eliminate harmonic components. In this case, [227] employs a null vector control technique with the conventional harmonic elimination PWM on two parallel VSCs to eliminate zero-sequence harmonic currents. Zero harmonics do not appear in line-to-line voltage, but they exist in each phase; so, in the case of parallel connection of inverters, they act as a zero-sequence harmonic voltage. This method decreases the zero-sequence circulating current, resulting in a decline in the related circulation power loss; however, it increases the switching loss.

Considering the low-frequency CM current, [228] continues studies on the test setup topology presented in [229]. A low-frequency CM voltage control loop to inject the duty cycle to the VSC is proposed. Split single-phase with grounded connection is applied on the AC side, whereas a bipolar DC-link with high grounding resistances is suggested for the DC side. The results confirm the DC-link voltage ripple decline. Also, in a hybrid system, [229] explains in detail how two-stage BIC can decouple the AC side ripples from the DC side noises. The test result confirms the stable operation of the proposed topology in different operating conditions of a rectifier, inverter, and transition. However, despite employing a low-frequency transformer at the PCC, the experimental results show low power quality and EMI noise in the ac voltage and current. Reference [18] proposes a two-stage interleaved BIC (AC/DC and DC/DC BIC) to decouple the CM voltage between the AC split-phase single-phase sub-MG and the bipolar DC sub-MG. The CM voltage control loop for DC/DC BIC is introduced.

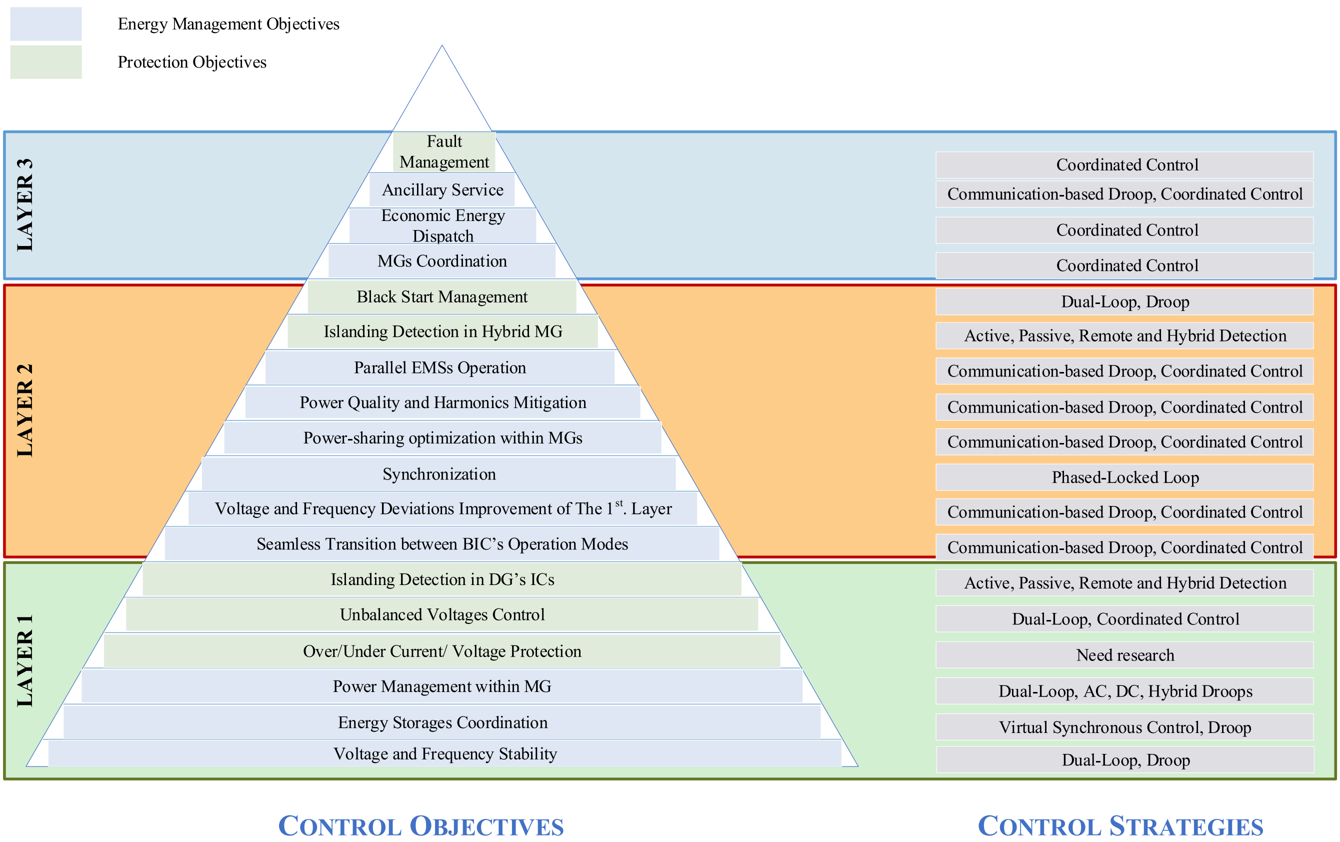


FIGURE 7. **Proposed Classification of hybrid MG control objectives.**

The power-sharing strategies contain the power factor objective implicitly by providing the required P and Q. THD and DC-links power quality are also considered in the power-sharing strategy. So most different control strategies for power-sharing can be used for power factor improvement, providing acceptable THD and suitable DC-link voltage as well.

Focusing on the role of AC/DC BIC's MPC in enhancing the power quality, [54] suggests using AC/DC BIC with DC sub-MG as a virtual active power filter. Implementing P-Q control in $\alpha\beta$ frame with MPC for AC sub-MG reference voltage, the required firing signals are produced. However, this study just focuses on power-sharing and THD as the power quality criteria. Studies in [118] focus on the required harmonics current control, whereas those in [119] address removal of low-order harmonics control of the current. Reference [118] suggests adding discrete-time filters in FCS MPC for a three-phase IC. The proposed cost function is the error currents in the $\alpha\beta$ frame. The discrete filter bandwidth can be tuned based on the desired output harmonics. Although the results confirm that load current harmonics are controllable by suitable discrete filter bandwidth, estimation of discrete filter coefficients in different load harmonics is a complicated task that is not covered in this study. Reference [119] proposes the two-step horizon hybrid FCS MPC in $\alpha\beta$ frame for current-controlled ICs with LCL filter. Then the results with the same hybrid FCS MPC but one-step horizon and hybrid FCS MPC with two PI loops are compared. The results confirm that the proposed hybrid FCS MPC provides better performance regarding the THD; however, the average switching frequency is also higher in this method. The low average switching frequency and quite low THD of the output current is one of the interesting results of this study. Also, the assumption and implementation of 40 k Hz sampling frequency compared to 5.5 k HZ average switching frequency makes it easy to do the state-space modeling, FCS MPC model, and delay issues.

To evaluate PWM techniques on the power quality, [230] considers a three-phase full-bridge VSC and compares different techniques of CM-current-reduction PWM. Unipolar, bipolar and hybrid PWM are studied and compared on a 1 kW VSC with a load with the unity power factor and with various modulation indices in [231]. The studied criteria are the inductor's THD current, CM current, and zero-crossing distortion. The results demonstrate the good performance of bipolar PWM in the CM current and zero-crossing distortion, whereas unipolar is suitable regarding THD and zero-crossing distortion. Hybrid PWM has a suitable function in the THD and CM current.

C. ISLANDING DETECTION

When unintentional islanding conditions, e.g., a fault in the main grid happens, the MG should recognize it and change it to work in the islanded mode. Islanding detection is applied to detect the instant at which AC/DC BIC should switch from the grid-tied to the islanded mode. Based on the IEEE 1547-2003 [232], Islanding Detection (ID) should be recognized within 2 s after it happens [233], [234] and IEEE 929-1988 [235] clarifies the requirements for ID [236].

The ability of hybrid MGs to restore is called a black-start, which needs some strategies discussed in [237], [238]. Voltage and frequency control and stabilization, power management are the main tasks of black-start management [237].

The core concept of ID methods is based on monitoring and detecting parameters (like frequency, voltage, harmonics, phase shift) change and deciding if an islanded condition happens [234], [236]. ID methods are divided into remote detection and local detection. Local detection techniques are also classified into passive ID, active ID, and hybrid ID [234]. Passive ID is based on the measurement of slope changes of the PCC parameters. A suitable threshold for ID is the main criterion to differentiate the islanding mode [233], [234].

In the active ID, the main concept is related to the perturbation and observation technique. In the grid-tied mode, the MG inertia is so high that perturbation cannot result in considerable changes; however, in the islanded mode, a noticeable change happens [233], [234].

The remote ID needs a communication network. The comparisons among different ID techniques are shown in TABLE 7.

In [239], the evaluation criteria for different performances of ID methods are classified into the following four groups:

- Non-Detection Zone (NDZ) is the indicator of failure regions that the method cannot detect the islanding condition properly. This zone is described in the power mismatch space (in passive ID) or load parameter space (active ID) [240].
- Detection time is the time difference between disconnection from the utility and detection.
- The error detection ratio represents the false detection ratio to the total detections.
- Power quality is inevitable in the distortion injection techniques.

The overall aim of this work is to categorize the MG's objectives, classify them among three layers of functions and their control strategy. Fig. 7 summarizes the general categorization of this work. It should be noted that despite the noticeable importance of BIC protection, only a few studies have addressed that topic. As a result, no proven strategies are available yet.

V. FUTURE PROSPECTS

A. REAL-TIME FLEXIBILITY CONTROL

The growing complexity of control systems due to the increasing integration of renewable energy sources in the power grid invokes a need for safer, faster yet reliable and economical testing methods, which do not compromise on the degree of detail [241]. The main disadvantage of typical analysis tools of MGs (software simulations, prototypes, and pilot projects) is the limited ability to test all interconnection issues, specifically in very small time steps [242]. In this context, real-time simulations and hardware-in-the-loop technologies are beneficial mainly because of their easily reconfigurable test environment and the possibility to determine exact values of control parameters and debug them [243], [244].

Some recent papers validate their methodologies in the control and optimization of hybrid AC/DC MGs through real-time simulation approaches [99], [245], [246], [247]. The study in [248] presented a comprehensive testbed for real-time multiagent systems for decentralized and distributed MG control. Authors in [249] also describe a range of possibilities for real-time MG testing. Real-time simulation is particularly beneficial for the comprehensive testing of interlinking converters of grid-tied hybrid MGs among the communication infrastructure and the protection system.

B. CYBERSECURITY

Cyber-physical systems, meaning integration of computation, communication, and physical processes as well as their security issues, are new research frontiers [250]. MGs are considered cyber-physical systems since they need advanced communication infrastructure to maintain their stability, therefore they are prone to cybersecurity issues as well [251]. Man-made incidents including cyber-physical attacks will significantly impact the stability and resiliency of the MG [252].

In the case of hybrid MGs, cyber-physical security and privacy issues would potentially have a significant effect on the central and distribution control structure. Therefore, advanced monitoring and real-time control systems for detecting attack scenarios and intrusion tolerance of these structures need to be developed in future research for the particular case of hybrid MGs.

C. UNBALANCED CONDITIONS CONTROL

From any unbalanced operation mode in PCC, faults, sudden load changes in the hybrid MG to misfunction of any capacitor or switches can lead to an unbalanced condition in the hybrid MG, e.g., an unbalanced voltage can lead to the unbalanced current, circulating current, and power loss in the hybrid MG. In this condition, providing a neutral point can help to provide a current path for unbalanced currents [258]. A fixed neutral point helps to prevent unbalanced and circulating currents, shifting the neutral point voltage, variable and unbalanced AC voltages, DC components in the AC side [258]. Four-leg VSC is the most common topology to provide a neutral point [151], [192]. The majority of researches have focused on the different control objectives in power management in symmetric sequences. So, asymmetric operation condition, especially in active power oscillation

TABLE 7. Comparison of ID techniques.

ID Methods	Applied Techniques	Advantages	Disadvantages	Ref.
Passive	Rate of change of transferred power with the utility Rate of change of frequency Rate of change of frequency over the power Change of utility impedance Harmonic distortions	Simple to implement Low cost Does not change the system's power quality Operates in less than 2 s	Large NDZs Almost high error detection rate	[234], [239] [253], [254]
Active	Disability in tracking reference reactive power Impedance measurement Phase shift (or frequency) Slide mode frequency shift Frequency drift	Small NDZ	Deteriorates the power quality The possibility of distortion signals interferences among multiple hybrid MGs	[234], [239] [253], [255]
Remote	SCADA Power Line Carrier Communication The signal produced by a disconnect	Almost Zero NDZ Needs less disturbance signal injection	Communication-based Lower reliability Expensive	[234], [239]
Hybrid	Combination of passive and active methods	Upgrade with signal processing analysis Low error detection ratio, Small NZD	Deteriorates less the power quality	[233], [234], [236], [239] [256],[257]

that has a direct impact on the DC-link voltage, is another important issue that needs to be studied [179].

The unbalanced condition originated from a fault condition and the required protection objectives are other topics for future research. Studies in [259] address the short-circuit detection in a back-to-back BIC. It employs a DC-link capacitor current change to detect the short-circuit. In [61], the parallel operation of BICs in an unbalanced grid fault focuses on stabilizing the DC-link voltage by supposing a redundant BIC. In [260], the current-controlled VSC in an MG in an unbalanced grid voltage and unbalanced fault condition is described, considering both the grid-tied and the islanded operation. The results show that the short-circuit current in the islanded operation mode is noticeably lower than in the grid-tied operation. Also, depending on the pre-fault IC condition (e.g., DG's generation), and fault type, the short-circuit current can be different in the direction, phase, and amplitude [260], [261]. All these aforementioned reasons make it impractical to implement the traditional protection functions like non-directional or directional overcurrent for the MG application in both the islanded and the grid-tied operation [260], [261]. In general, it is required to enhance the existing protection system to categorize the solutions in the future research into the following three solution categories: adaptive protection, communication-based protection, and customized logic-based scheme [261], [262].

D. TRANSITION MODE OF BIC

Transition mode can be divided into two categories: 1- from standalone to grid-tied connection or vice versa; 2- from inverter mode to rectifier, or vice versa. The former arises due to different control strategies; in the standalone mode, droop and voltage-controlled mode control and grid-tied current-controlled mode are implemented [179]. Through the transition mode, these two control systems should shift to each other. This control transition may produce inrush current and resonance in output filters [43]. Two parallel AC/DC BICs [43] and fault limiter implementation [179] can be solutions here; however, no studies have proven their realizations in hybrid MG yet.

In the interchange between the rectifier and the inverter mode, the BIC current should be shifted in the other direction, which also means different control strategies.

In general, minimization of inrush current and the smooth transition currents and voltage for both groups are the main concerns requiring research.

E. ROBUSTNESS ANALYSIS

The variation or imbalanced condition in line and filter impedance may happen in practice, so the control system has to have minimized sensitivity toward the inputs of these disturbances. The robustness analysis for changes in line impedances and LCL filters was conducted for the $H\infty$ proposed controller technique and compared with the MPC technique in [94]. Also, both singular value decomposition (used for indicating the process noise index) and the bode analysis were performed to confirm the decomposition of system's singular value and phase margin to tolerate noises. The results show that the $H\infty$ controller is more robust than MPC. Another study of control parameter roles in the stability of the current-controlled grid-tied inverter in the grid impedance variation condition was conducted in [161]. The decomposition method clarifies the stable region in the z domain in the grid impedance uncertainty. To the best knowledge of the authors, little research has been done in this field. The robustness analysis of the influence of the communication system variables, e.g., the delay time in the communication-based control methods, is another research gap. As these conditions can happen, it is required to address them and to confirm experimentally.

F. CM CURRENT CONTROL

Low-frequency CM leakage current referred to as ground leakage current [228] is one of the issues that connects AC sub-MG to the DC sub-MG, which is dependent on both sides of the grounding system. This CM current increases power loss and safety issues. Many studies have focused on the decline of the high-frequency EMI and the control of the power quality in the inverter mode of BIC such as PV connection. However, few studies have addressed the frequency noise and power quality in the rectifier mode of BIC on the DC side. Decoupling the AC side from the DC side by the two-stage BIC is an efficient way to decline the effects of EMI [229]; however, few studies consider the effects of AC side power change on the DC-link ripple and the harmonics produced [27]. This issue originates from an essential topic, i.e., lack of DC power quality regulations. Although some studies address the issue of DC power quality, the lack of a unit standard is a major topic. For instance, in [263] DC power quality evaluation is based on IEEE 1159 [264] and [265] points out some main criteria of DC power quality, but there are no common criteria to evaluate harmonics, EMI, DC-link ripple, CM voltage, etc.

VI. CONCLUSION

The growth of DGs is the main motivation to enhance the traditional grid to the MG, and the increasing rate of DC loads and sources is the main reason to choose the hybrid MG. The focus of this review was on the different control functions of BIC in the hybrid MG. The most studied function is power-sharing. Different control strategies toward power-sharing were investigated and categorized. The common power sharing strategy, which is droop, was classified based on AC, DC, or both types of energy, availability of the communication system, and coordinated control. Different techniques for different strategies of power-sharing function were compared, the PID+R controller technique is the most mature and widespread, whereas digital processor improvement opens a new door to apply heavily processing control techniques in a shorter time. In this way, different MPC techniques are the trend in the past eight years. Different MPC techniques have been implemented in power-sharing to find the optimum MPC control structure with optimized prediction horizon steps and weighting factors. Also, the RL technique is an interesting newcomer technique needing more research. Power variations interactions on the AC sub-MG and DC sub-MG in the presence of filter and line impedance disturbances are the other main issues to be implemented in practice.

However, despite the developed concept of the hybrid MG, it is evident that the main limitation consists in the low power rating of BIC. Our analysis demonstrated that the most typical power rating of the commercially available BICs is 10 kW, which is far from the power distribution scale. As a result, a major improvement in the wide bandgap technology, such as SiC and GaN, is required to improve the capability of the BICs and ICs applied to a large power scale.

DC-link capacitors are one of the weak points of the hybrid-MG with one-phase AC/DC BIC, which decreases its reliability. The first solution is an enhancement in capacitor technology with high operating temperature and high capacity with small volume. The other solution is to find control techniques to separate double ripple frequency power in the DC-link. Results of different control studies have not yet provided overall solution to the issue.

CM voltage and current control in different operating modes, especially in unbalanced conditions, designing the optimized grounding circuit and EMI noise control as well as protection strategies are the future topics to be addressed.

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