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A Comprehensive Review on Power Converters Control and Control Strategies of AC/DC Microgrid

SHAMSHER ANSARI[1], ASEEM CHANDEL[1], (Senior Member, IEEE), AND MOHD TARIQ[2], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Rajkiya Engineering College, Mainpuri, Mainpuri 205119, India
[2]Department of Electrical Engineering, Zakir Husain College of Engineering and Technology (ZHCET), Aligarh Muslim University, Aligarh 202002, India

Corresponding authors: Shamsher Ansari (way2ansari214@gmail.com) and Mohd Tariq (tariq.ee@zhcet.ac.in)

ABSTRACT Owing to the smart lifestyle, environmental consciousness, and dwindling fossil fuel supplies, there is a huge demand for clean and green energy. Microgrid (MG) is a crucial approach to renewable and clean energy. Because of the success of the AC utility grid and the growing demand for critical loads, it is very convenient to provide AC/DC MG that can easily satisfy both the alternating current (AC) MG and the direct current (DC) MG requirements. Due to uncertainty in load variations, main grid failures, intermittent power generations from renewable energy sources (RESs), the synchronization and interconnection of different power converters are the paramount issues in the control of AC/DC MG. This article presents an overview-oriented state of the art in the recent advancement in control strategies of AC/DC MG and its associated power converters control. Based on recent research, this article summarizes unobstructed views on different topologies, types of power converters, power converter controls, and control strategies of AC/DC MG. Finally, it identified some future challenges that need to be addressed in order to develop a sustainable and reliable control strategy for AC/DC MG. This article will serve as a guide for researchers.

INDEX TERMS Distributed generation, microgrids, AC/DC microgrid, centralized control, decentralized control.

I. INTRODUCTION

MGs compromise different RESs, i.e., PV cells, windmills, energy-storing systems (ESS), diesel generator sets, and small hydropower plants, as discussed in the [1], [2]. With the advancements in power semiconductor devices, the integration of RESs with leading utility or MG becomes so more accessible. Based on the adopted topology, there are three types of MGs, classified as DC MG, AC MG, and AC/DC MG or hybrid MG [3]. The DC MGs are preferred to supply critical loads like computers, operation theatres, and billing counters. Whereas the AC MGs are preferred in supplying all loads during off-grid or on-grid. The AC/DC MG possesses the characteristics of both DC MG and AC MG. Since begin, in these types of MGs, the power converters are connected in parallel with the MG bus-bar and belong to the parallel topology of MG. Recently a series–cascaded MG topology is being investigated. Inam Ullah Nutkani and *et al.* in [4] has presented a series- cascaded AC MG topology to integrate the non-dispatchable RESs to the MG and offered its advantages and disadvantages over the parallel topology. Fig.1 shows the different topological advances of MGs. Based on the surpluses of power in the main grid/microgrid and to utilize the maximum capacity of RES, the MGs are empowered to operate in two modes, namely; 1) Islanded (IS) or OFF-grid mode and 2) Grid-connected (GC) or ON-grid mode. In IS mode, the microgrid works with its own set-value of frequency and voltage, whereas, in GC mode, the MG has to follow the line frequency and the line voltage of the utility grid. There is another mode of operation, i.e., Transition periods, which is dynamic between IS mode and GC mode or vice-versa. During this period, all the elements present in the MG have to experience abnormal voltage and frequency variations, which cause power quality and stability problems in the MG. The solution to these problems has been presented in many researchers' works. Huang *et al.* [5] presented a reasonable multi-level inverter-based dynamic voltage restorer (DVR)

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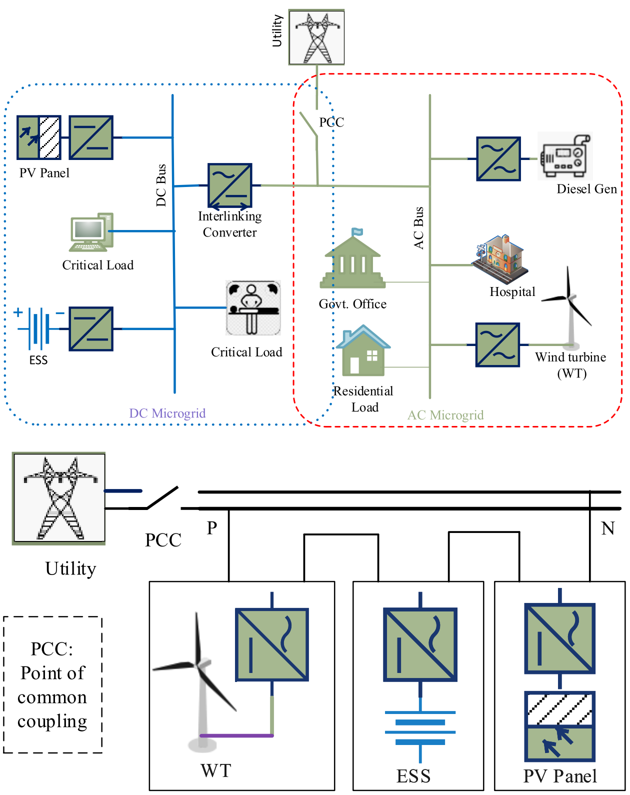

FIGURE 1. (a). AC/DC MG based on parallel MG topology. (b). AC MG based on series-cascaded MG topology.

model to address the power quality problems caused during the transition periods. F. Harirchi *et al.* presented a unified control-based smart inverter to smoothen transitions of MG caused due to switching of voltage or current controllers [6]. J. Wang *et al.* developed MG transition controller-I & II for the smooth transition of MG under normal and abnormal conditions [7], [8].

Power converters assume a significant job in interfacing different types of RES and ESS to the MG and utility grid. Depending on the shapes of the generated power from RESs, these converters could be either AC/DC or DC/DC types for DC MG and DC/AC or AC/AC type or Matrix converter for AC MG. In the case of AC MG, the power inverters play a significant role in interfacing the RESs to the MG bus-bar. These power inverters are designed to operate as either type voltage source inverter (VSI) or current source inverter (CSI). The VSIs are supposed to provide correct voltage and frequency into the MG, whereas the CSIs are supposed to inject current into the MG. Many researchers have presented much advance power converters for MGs [9]–[13], which are not only ensuring the primary role of power converters but also other functions, i.e., fault current handling [11], harmonics suppression, power quality improvement [12], efficiency improvement [13], to make the MG more reliable and sustainable powerhouse. The research works carried out in the literature [14], [15] shows the advantages of DC MG over AC MG in terms of reliability, efficiency, protection schemes, and stability. Accordingly, we must have AC / DC MG, which reduces the number of power converters and offers efficient performance, lower capital, and operating costs with more natural compatibility with AC or DC loads. We know that there are enormous uncertainty in load variations, main grid failures, power generations from RES, and unequal power-sharing among DGs. So, AC/DC MG is pretty challenging to synchronize and monitor. Therefore, AC/DC MG needs a sustainable and reliable operation and control strategy. To inspire and promote work to establish a secure and effective AC/DC MG control strategy. Many researchers published numerous reviews on control strategies. The researchers in literature [16], [17] presented a systematic review of the primary and secondary control strategy of DC, AC, and AC/DC MG until 2017. Further, a review on power quality control is presented [18], which has discussed the role of different controllers in compensating and improving the power quality of AC/DC MG. S. Bayhan *et al.* [19] have presented a review on power converters' topology advancement and its control strategy, but it did not discuss the PQ control and V/f control.

Further, the literature [20] presented a review on advancement in basic control strategies of AC/DC MG till 2018 and a similar review article submitted in writing [21] without discussing on the multi-agent system (MAS) and Model Predictive Control (MPC) based control strategy till 2018. Arfeen ZA *et al.* presented an overview-oriented literature review on control strategies of MG in literature [22], where a few latest references were discussed. Thus, there is a need to conduct a literature review on power converters control and control strategies of AC/DC MG.

This article proposes a contemporary review on controlling the power converters and control strategies of AC/DC MG. The structure of the article is as follows: In section-II classifications of power converters are presented, and in Section III, a state-of-the-art review on power converter control and control strategies of AC/DC microgrid is presented. Further, in section-IV and section-V, the comparative summary, conclusion, and future challenges are pointed out, respectively.

II. POWER CONVERTERS IN AC/DC MG

The power converters in AC / DC MG can be categorized as indicated in Fig.2 on the basis of operational conduct.

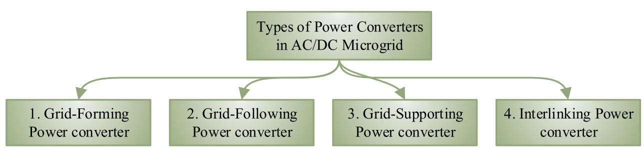

FIGURE 2. Classifications of power converters in AC/DC MG.

A. GRID-FORMING POWER CONVERTER

These power converters are mainly related to the ESS units in AC/DC microgrid. In IS operation, these power converters are

TABLE 1. Comparision of the power converters.

Features contributed to the MG	Grid-forming power converter	Grid-feeding power converter	Grid-supporting power converter	IPC
Source type	Controlled voltage source	Controlled current source	Controlled voltage/ current source	Controlled voltage/ current source
Output impedance	Low	High	Non-zero, finite	Finite
combination	Series	Parallel	Series-parallel	Series-parallel
Power converter control	constant V/f control (in case of AC) and Constant voltage control (in case of DC)	PQ control (in case of AC sub-grid) and Current or power control (In case of DC sub-grid)	Droop control (P/f and Q/V droop control in case of AC sub-grid) and V-I or V-P droop in case of DC sub-grid)	Bi-directional Droop control
Associated with	Dispatchable sources, i.e., ESS	Non-dispatchable sources, i.e., PV, Wind, etc.	Generally, Dispatchable sources	Two sub-grids
Output voltage and frequency	Fixed	Synchronized with sub-grids	Regulated	Regulated
application	IS	GC	Both IS/GC	Power exchange
Power flow control	Two-way	One way	Mostly two-way	Two-way

accountable for maintaining reference voltage and frequency in the case of AC sub-grid and reference voltage in the case of DC sub-grid. In GC operation, these power converters adjust the active power (in case of DC sub-grid) and active & reactive power (in case of AC sub-grid) to keep-up the state of charge (SoC) of the ESS units and, at times, to enhance the voltage profile (in case of DC sub-grid) and power quality (in case of AC sub-grid) [23]. Therefore, these converters considered as a current-controlled voltage source consisting of low impedance in series [24], [25]. These converters are assumed to be operated in voltage control mode (VCM) so that the voltage and frequency (in case of AC sub-grid) or voltage (in case of DC sub-grid) control can achieve [26]. These converters find full applications in centralized control operated MG.

B. GRID FOLLOWING POWER CONVERTER

These types of power converters are associated with the non-dispatchable distributed generations (DGs), i.e., solar panels, windmills. These converters continuously follow the grid reference voltage and frequency in the case of AC sub-grid and inject active and reactive power to achieve unity power factor. In the same way, in the case of DC sub-grid, it injects current or power into the grid while following the grid reference voltage [23]. Though these converters follow the grid reference values, so this type of converters are treated as a controlled current source consisting of high impedance in parallel. However, these converters do not participate in power balancing and are easily installable in parallel with other grid following converters. Since these converters inject current into the sub-grids while following the grid reference values, it shows similar behaviour to the MG in GC or IS mode [24], [25]. However, these converters are unable to act in IS mode without the support of grid-supporting power converters or local synchronous generators. These converters are assumed to operate in current control mode (CCM) or power control to achieve active and reactive power control (in case of AC sub-grid) and current or power control (in case of DC sub-grid) [26].

C. GRID-SUPPORTING POWER CONVERTER

Sometimes the grid-forming power converters are failed to maintain the pre-assigned voltage and frequency in the sub-grids due to limited reserve capacity of power to be delivered or absorbed by the ESS units. So, some additional dispatchable DGs or ESS units used to support the grid forming converters to retain the assigned voltage and frequency (in case of AC sub-grid) and assigned voltage (in case of DC sub-grid) [23] in IS mode. These converters are considered equivalent to a controlled voltage source/current source associated with a low/high impedance in series/parallel, respectively [24], [25]. In GC mode, these converters provide support for improving the power quality (in case of AC sub-grid) and voltage profile (in case of DC sub-grid). These converters can operate in both VCM or CCM and realize the droop control strategy. However, these power converters offer low inertia to the MG due to which MG becomes prone to instability. Many research works conducted to provide a solution to this problem by introducing and modifying the concept of virtual synchronous generators [27], [28] or virtual inertia devices [29].

D. INTERLINKING POWER CONVERTER

The interlinking Power converter (IPC) is generally used to interlink DC sub-grid with AC sub-grid to form the AC/DC MG. These converters are capable of bidirectional operation based on the surpluses of power on a particular sub-grid. It can operate in inversion, rectification, and or stop mode. Due to recent advancements in power converters, the IPCs are also capable of multigrid connections. The thrilling functionalities of the IPCs are; the coupling of sub-grids irrespective of the nature of the grid, power flow control, ancillary services, reduces the complexity of the power networks, enhances the stability of the AC/DC MG. Many works suggested that IPCs can also fulfill the purpose of grid-forming and grid-supporting power converters [30]. However, the literature [31] presented some severe issues such as 1) non-linear load behaviour while performing power flow from AC sub-grid to DC sub-grid, 2) circulating current between parallel operated IPCs and 3) re-synchronization issue after faults clearance. Further, the use of IPCs for ancillary services like power quality improvement by limiting the power exchange between the sub-grids may decrease the maximum utilization of RESs that means reduces the system efficiency. Hence there is a tradeoff between conversion quality and system efficiency [32].

III. CONTROL STRATEGIES OF AC/DC MG

Many researchers worked on the issues incorporated with interfacing the MG to the main grids, and solutions have been presented in the literature [33]–[36]. During the operation of the microgrid in either IS/GC mode or transition periods. The common challenges faced by MG operators/ engineers are unequal load sharing, power quality issues, synchronization failure, safety concerns, protection issues, stability problems. Since the start of the twentieth century, much research work has been carried out in control strategies of power converters and control strategies of MGs to rectify the above-cited challenges. The control strategies of power converters and AC/DC MG could be classified as displayed in Fig.3. A detailed, up-to-date literature analysis is presented in further sub-sections for the formulation of current research challenges in the operation and control of AC/DC MG.

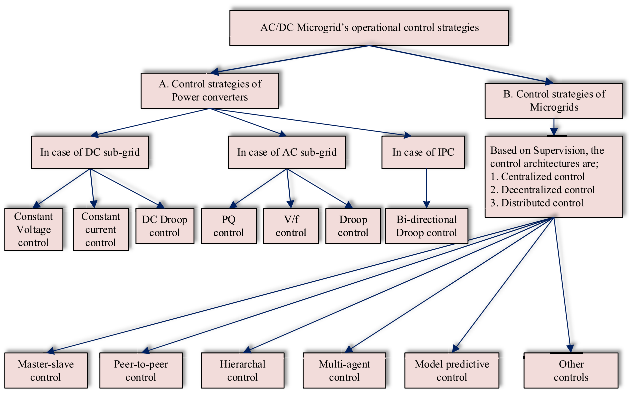

FIGURE 3. Classification of Control strategies of AC/DC MG.

A. POWER CONVERTERS CONTROL IN AC/DC MG

In general, the micro-sources are connected to the AC/DC MG bus bar through different types of voltage source converters. The control strategy adopted to control the power output of the power converters is known as local control / primary control or power converter control. This level of control strategy plays a crucial role in enhancing system performance, stability, accurate power/load sharing in the presence of non-linear loads, enabling plug-and-play operations by DGs, eliminating circulating currents, etc. In the case of DC sub-grid, the commonly used power converter controls are constant current control, constant voltage control, and DC droop control. Similarly, in the case of AC sub-grid, the standard power converter controls are PQ control, V / f control, and Droop control. Further, Bi-directional droop control in the case of IPC.

1) CONSTANT VOLTAGE CONTROL

To keep the DC bus voltage (V_T) stable, this control strategy employed with grid-forming converters [37]. As shown in Fig.4, at first, the V_T compared with the reference voltage(V^*) and the error exported to the proportional-integral (PI) controller for generating the reference current (I^*). Further, The I^* and converter output current (I_c) compared and the error processed through PI controller and pulse width modulation (PWM) to regulate the DC bus voltage.

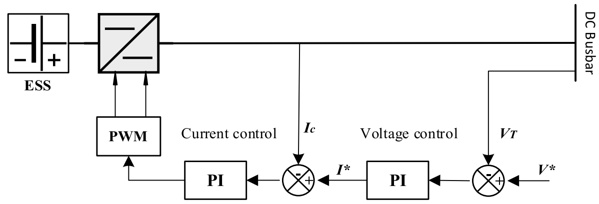

FIGURE 4. Block diagram of constant voltage control in case of DC sub-grid.

In this control strategy, the ESS units must have sufficient capacity to handle the precarious power balance in the DC sub-grid. However, this control shows poor performance with the constant power loads (CPLs) containing negative incremental resistive characteristics, and hence its consequences instability in the DC bus. Nevertheless, the research works carried out in the literature [38], [39] proposes a sliding mode controller (SMC) based voltage control to reduce this instability. Further, the literature [40] purposes robust constant voltage control of mitigating the instability issue with uncertain CPLs.

2) CONSTANT CURRENT CONTROL

This control mainly associated with grid-connected grid-feeding converters and accountable to maintain constant terminal current from the micro-sources. This control, also known as constant power control [41]. As shown in Fig.5, this control contains two loops one is the current control loop, and the other is the power control loop. In the case of non-dispatchable sources, the reference current imported from MPPT control and constant current control is achieved. The power control loop is used with the unit in exceptional cases. For example, the required power is too low or high, which may cause severe voltage fluctuation in the DC bus. In such a case, the power control loop generates the reference

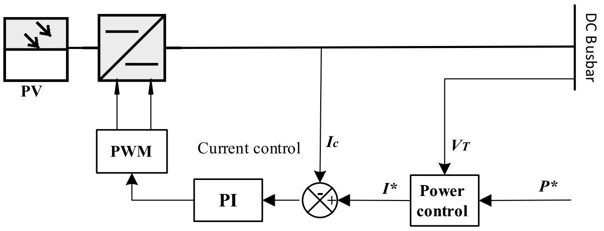

FIGURE 5. Block diagram of constant current control in case of DC sub-grid.

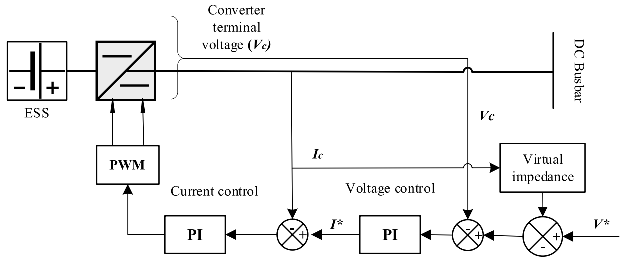

FIGURE 7. Illustration of virtual impedance-based droop control.

current and commands the ESS unit to release/ absorb the power to stabilize the DC bus voltage [42].

3) DC DROOP CONTROL

Initially, the concept of droop control was developed for AC MG. Later it successfully employed in power converters present in DC MG to control and equalize the load current sharing among the parallel operated converters according to their generation capacity. The main objective of adopting this control strategy is to safeguard the islanded MG against continuous load variations by adjusting the droop characteristics of the DGs. In the case of DC MG, the parallel operated converters consist mainly of two types of droop characteristics current /power mode droop and voltage mode droop. The current /power mode droop includes I-V droop and P-V droop, while voltage mode droop includes V-I droop and V-P droop [43]. The mathematical relation of these droop characteristics is given below;

$$V_{ci} = V_T - m_{Ci} I_{ci} \tag{1}$$

$$V_{ci} = V_T - m_{Pi} P_{ci} \tag{2}$$

where V_{ci}, I_{ci} and P_{ci} are the output voltage, output current, and output power of the i^{th} power converter, respectively. m_{Ci}, m_{Pi} are the droop coefficient in the respective droop control.

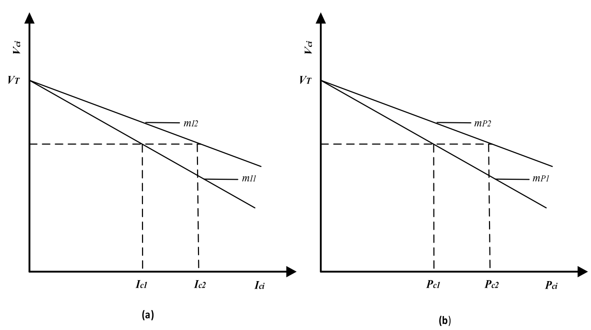

FIGURE 6. (a) V-I droop characteristics (b) V-P droop characteristics.

However, these are very conventional droop control methods and possess two serious issues; first, less accuracy in power-sharing due to unequal line impedance and second reduced output voltage than the reference voltage. Generally, the use of higher droop coefficient DGs can improve the current sharing accuracy, but consequently, it increases the voltage deviation. By inserting the virtual impedance (see Fig.7) with the droop controller, the current sharing performance improved significantly [44]. The involvement of no communication is the main advantage of droop control. Still, some researches involved a low band communication channel in enhancing the performance of droop control as well as the entire microgrid [45], [46].

The recent research studies on adaptive droop control, proving versatile [47]–[49]. The adaptive droop control presented in the literature [47] enhanced the current sharing among the ESS units; further, the abstract [48] shown mode adaptive droop control, which improves load-current sharing with proper voltage regulation and decreases the circulating currents among the DGs. The circulating currents exist between the DGs mainly due to mismatch output characteristics, and it results in poor performance of the converters. Ghanbari and Bhattacharya [49] presented a secondary controller with the adaptive droop control to suppress the circulating current and line parameters effect, and their presented results show accurate current sharing among the converters with the reduced circulating current. The virtual frequency-based droop control provides excellent performance, but it involves a low bandwidth communication channel and makes the system fault ride through [50].

4) PQ CONTROL

The primary purpose of using PQ control [51] is to maintain constant active power and reactive power at micro-source terminals when the frequency and terminal voltage fluctuates within the recommended limits. At first, PQ control decouples the active and reactive power to accomplish autonomous control, illustrated in Fig. 8. The P controller intent to keep up active power constant at the given reference value within the acceptable frequency range. The Q controller intent to keep up reactive power output constant at the given reference value within the acceptable terminal voltage range.

However, this control technique does nothing to keep up the terminal voltage and frequency constant. So, an additional distributed generator is adopted to regulate the terminal voltage and frequency of MG within the prescribed range. In GC mode, the utility grid is liable to retain the terminal voltage and frequency of the MG. As presented in Fig. 8 and the literature [52], the PQ control is supposed to be a grid voltage adapted PQ decoupled control technique. Wherein the outer loop performs power control, and the inner loop

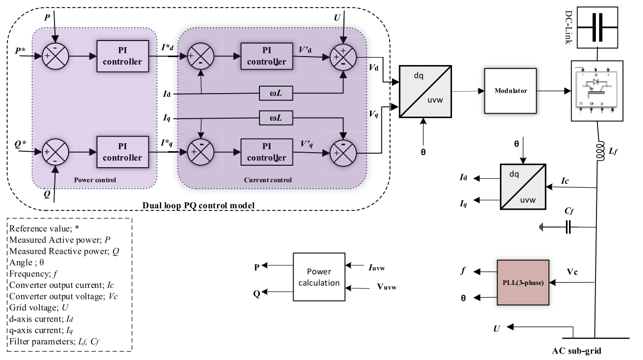

FIGURE 8. Illustration of PQ control.

performs current control. The control pulses for the VSI can be derived using reverse park transformation of d-axis and q-axis voltages. Further, the three-phase voltage output of the VSI can be obtained by sinusoidal PWM. The literature [53] investigated and applied different types of optimization techniques, i.e., Particle swarm optimization (PSO), Genetic algorithm (GA), Artificial bee colony (ABC), and PSO with new update mechanism (PSOd), for optimizing the gain of the Proportional plus integral (PI) controller adopted in the PQ control scheme. This research pointed out that the ABC optimization technique provides higher optimization of PQ controlled microgrid.

5) V/f CONTROL

In 2002, Barseli and his fellow authors were first to introduce the concept of V/f control for the DGs operating in islanded MG for retaining frequency and terminal voltage within the assigned reference value. However, this control scheme was unable to respond to the load variations. The primary intent of using V/f control is to make available constant terminal voltage and the frequency at inverter output, irrespective of the actual active & reactive power output of the DGs in order to secure the continued operation of the slave DGs and sensitive loads operating in islanded mode. In this control [51], a frequency controller used to adjust the real power output to preserve the frequency within the pre-assigned limit and a voltage controller to improve the reactive power outputs to retain the terminal voltage within the pre-assigned limit. Fig.9 illustrates the V/f control, where the outer loop performs the voltage control, and the inner loop performs the current control [52]. The outer-loop control aims to maintain the steady voltage output, whereas the inner-loop control creates the current servomechanism system to automatically speed up the dynamic operation in order to secure against the disturbances. The inner-loop control enhances the bandwidth of the inverter control system and thereby speed-up the dynamic response and adaptability of the inverter to non-linear load disturbances and finely reduces the THD of the output terminal voltage. Hence, the concepts of dual-loop control ensure the best usage of system status information and provide high dynamic

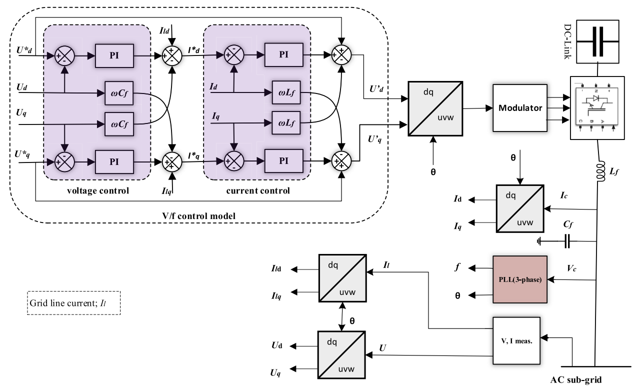

FIGURE 9. Illustration of V/f control.

performance and steady-state precision. However, the V/f control is very identical with the PQ control in terms of control and decoupling system. Beiming Liang and *et al.* improved the stability and reliability of an AC/DC MG by adopting the PQ control for the IPC in GC mode and applying the V/f control for the entire system in IS mode [54].

The literature [55] presented a coordinated control of PQ and V/f control strategy to improve the dynamic stability response of an islanded multi DGs AC MG and uses the mutation-based improved firefly algorithm (MIFA) technique to optimize the system.

6) DROOP CONTROL

The main objective of adopting this control strategy is to safeguard the islanded MG against continuous load variations by adjusting the droop characteristics of the DGs. The MG DGs usually consist of two droop characteristics, i.e., the P/f droop and the Q/V droop characteristics. Therefore, this control strategy can be separated as active power control and voltage control. The active power control is achieved by adjusting the operating point of P/f droops according to the deviation of frequency caused by the load variations. The equation (3) establishes the droop relation between actual power output and frequency.

$$\Delta \mathrm{P} = P_2 - P_1 = \frac{f_1 - f_2}{S_p} \tag{3}$$

where ΔP indicates the change in active power output of the DGs and S_p indicates the slope of the V/f droop curve, as depicted in Fig.10(a).

The voltage control can be obtained through regulating the reactive power output of the DGs following the load variations. The reactive power and terminal voltage (V_T) are mathematically related as follows;

$$\Delta Q = Q_2 - Q_1 = \frac{(V_{T1} - V_{T2})}{S_q} \tag{4}$$

where the ΔQ and S_q indicates the change in the reactive power and the slope of the Q/V curve, respectively, as depicted in Fig.10(b).

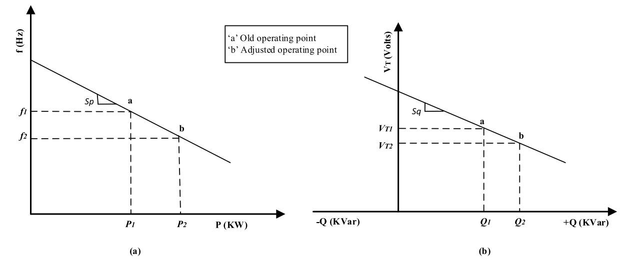

FIGURE 10. Represents (a) V/f droop (b) Q/V droop characteristics of DGs.

However, this scheme possesses poor performance in reactive power-sharing among the DGs. The literature [56] presented an auxiliary controller to damp out the oscillation caused due to droop gain and improve stability and reactive power-sharing among the DGs of MG. Somewhat these problems sorted out in the research works carried out in the literature [57], [58]. Besides, the novel [59] introduced a droop controller by establishing a droop relationship between temperature and power output with the help of an electro-thermal model of power converters in order to distribute the thermal distribution between parallel power converters equally. The presented result ensures the interchangeable thermal stress among the power converters and enhances the operating life span of the power converters. The literature [60] introduced a revised droop control scheme to control power-sharing among ESS units while discharging through islanded MG. The research [61] presented a dual droop controller to balance SoC among different capacities of ESS units in islanded MG to ensuring power quality by eliminating the effect of capacity on initial SoC.

The literature [62] presented a droop based proportional active and reactive power-sharing scheme for PV dominated islanded AC MG. This scheme is quite robust against disturbances in the load, the effect of start-up transients, and unpredictability of the PV generation. Recently several researches have been conducted on the adaptive droop control strategy for both DC MG (see A.3) as well as AC MG [63]–[67]. Figure 11. illustrate virtual impedance-based adaptive droop control in AC MG. Primarily this strategy minimizes the current sharing difference and the circulating current among the power converters connected in the MG [64]. So further, this control strategy investigated by many researchers for loss minimization [65], power-sharing management [66], and efficiency enhancement [67] of MG.

7) BI-DIRECTIONAL DROOP CONTROL

The IPCs plays a crucial role in maintaining stability and power exchange in AC/DC MG. The bi-directional droop control measures the degree of demanded power according to the AC sub-grid frequency (f_{AC}) and DC sub-grid voltage (U_{DC}). Accordingly, it determines the direction and magnitude of the potential to be transmitted through the IPC from AC sub-grid to DC sub-grid or vias versa [68]. In this control, f_{AC} and U_{DC} are considered as input variables to control the active power to be transmitted through the IPCs. However, this control possesses poor reliability caused due to decline of f_{AC} and U_{DC} by droop control. Fig.12 illustrates the bi-directional droop control of IPC in AC/DC MG [69]. It consists of f_{AC}-U_{DC}-P droop controller followed by the power-current control loop. The recovery control presented to compensate for the effect of the decline of f_{AC} and U_{DC} by droop control and improved the reliability of the control strategy. Further, the virtual impedance-based bi-directional droop control presented to achieve a high level of power-sharing [70].

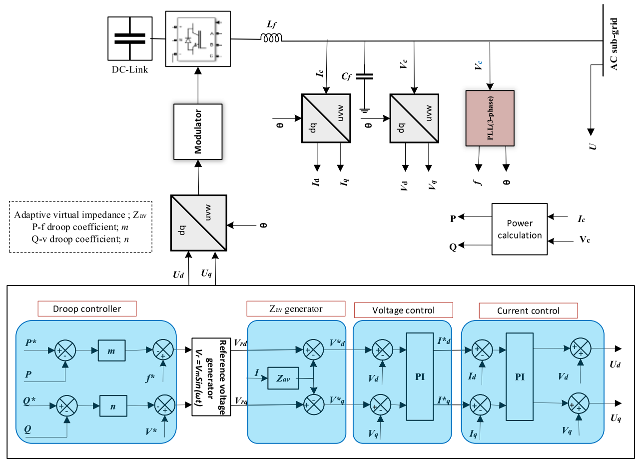

FIGURE 11. Illustration of adaptive virtual impedance-based droop control.

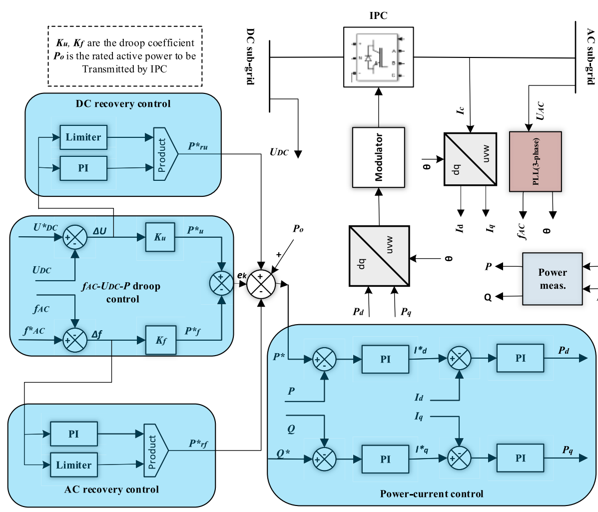

FIGURE 12. Illustration of Bi-directional droop control of IPC.

Literature [71] presented a dual droop controller with a data-driven model-free voltage controller to resolve the power-sharing issues of an interconnected AC/DC MG.

Further, the literature [72] presented a dual droop control strategy for the interlinking converter to enhance the power-sharing between the DC MG and the AC MG in an AC/DC MG. The literature [73] presented event triggering-based droop control for IPC to balance power-sharing between AC MG and DC MG in an AC/DC MG.

Further, the literature [74] presented an incremental cost-based droop control for improving the feasibility and economical operation of any topological MG (AC, DC, or AC/DC). Also, the literature [75] presented a quasi-proportional resonance (PR) based droop control scheme for suppressing harmonics and improving the economical operation of the AC/DC MG. The literature [76] constituted a V^{d}vs. f^{ac} droop and presented a cost-based droop control strategy for the IPCs used in AC/DC MG to coordinate power exchange and achieve global convergence of incremental cost between the MGs.

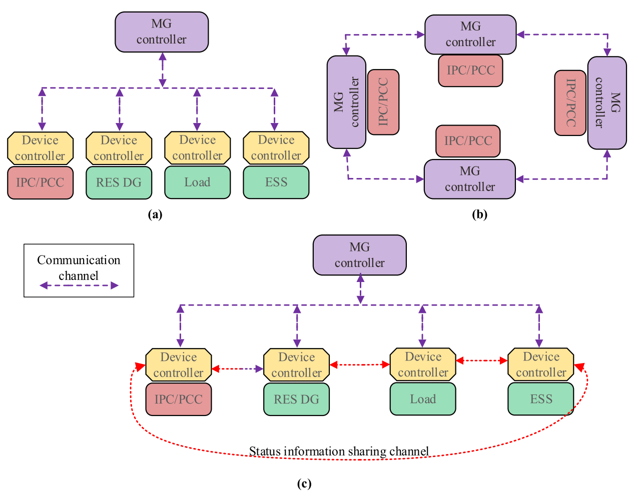

FIGURE 13. Representation of control architectures MG; (a) Centralized Control, (b) Decentralized Control and (c) Distributed Control.

B. CONTROL STRATEGIES OF MGs

The control strategy of the MG is nothing but controlling, monitoring, and coordinating the different control strategies of power converters used to interface RES or ESS units into MG. Due to the existence of various sorts of DGs, ESS, and power converters in an AC/DC MG, it is quite difficult to operate an AC/DC MG. Therefore, the control strategy of MG is a vibrant topic for the researchers. However, the adopted control strategies must ensure the following aspects; 1) balanced load-sharing among DGs according to their capacity. 2) equal harmonic current sharing among the DGs. 3) stable transition of operating modes. 4) synchronization with protective elements. 5) maintaining constant terminal voltage and frequency within the prescribed limit. Etc. Based on supervision, how status information is collected, and the decision-making process, there are three different control architectures, namely centralized control, decentralized control, and distributed control. Fig. 13 illustrates the concept of centralized control, decentralized control, and Distributed control architecture. In the centralized control architecture, the MG central controller (MGCC) behaves like the brain of the MG control system. It gathers the status information from different parts of the MG via a wired or wireless communication system. Accordingly, it makes the decision and supervises the DGs, ESS units, and controllable loads to control and monitor the entire MG. Continuously, it upgraded the control procedure according to the operating conditions of the MG bus-bar and guaranteed the smooth exchange between grid-connected, islanding, and shut-down [52]. In decentralized control architecture, each micro-controller is considered to be autonomous, but these all together form a network of peers that speaks for the entire power system. To defeat the absence of the MGCC, the peers interact together to share their local status information. Based on this local status information, any decentralized controller can make precise control decisions in any specific circumstance [77]. The centralized control architecture widely depends on the communication system, so even a minor fault in the communication system is sufficient to shut-down the entire system. Whereas, the decentralized control architecture, fewer depends on the communication system and only faulty part of the system gets affected due to any fault in the system. In distributed control architecture, the status information of the micro-terminals is allowed to share among them and maybe a central controller used in order to make the decisions. This control architecture incorporates the advantages of the centralized and decentralized architectures of control. Further, we categorize the control strategies of MG as Master-slave control, Peer-to-peer (P2P) control, Hierarchal control, MAS-based control, MPC-based control, and other controls, as depicted in Fig.3. An up to date review on these control strategies has been presented in the further sub-sections.

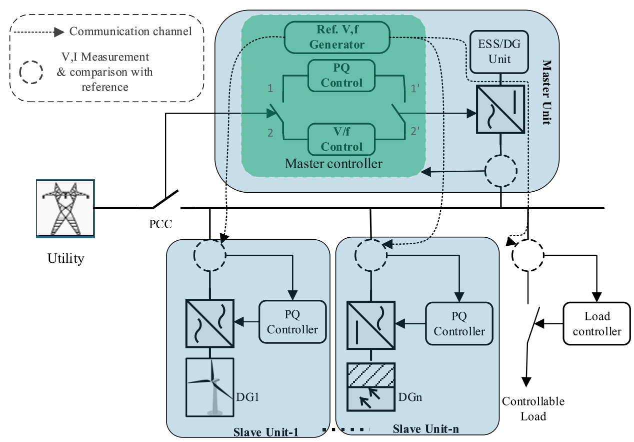

FIGURE 14. Architecture of Master-slave control strategy in MG [51].

1) MASTER-SLAVE CONTROL STRATEGY

Fig. 14 illustrates the master-slave control strategy of the microgrid. In this control strategy, one or more DGs or ESS units can behave as a Master unit while the other DGs or ESS units as Slave units. The master unit/units is/are capable of partially controlling the Slave Units. In GC mode, both the master unit and slave units operate under the PQ control, and the utility grid provides the reference voltage and frequency. In IS mode, the master unit adopts the V/f control to provide reference voltage and frequency to the slave units operating in PQ control [51], [78], [79].

The research works presented in the literature [80], [81] suggesting the selection of one DG as a master unit to make smooth regulation of voltage and frequency so that MG can work for a long time in IS mode. Some other researchers also suggested the use of both ESS and DG together as a master unit. Because of the continuous discharging of the ESS unit in IS mode, the ESS unit alone cannot be used as a master unit for a long time. However, if the ESS unit reserves sufficient energy, then it can perform like a master unit under the V/f self-control. Afterward, it supposed to make available the reference voltage and frequency to the islanding MG and regulate the output power to fetch back the voltage and frequency to the reference value. If the ESS reserves limited and tiny energy, then the DC-link of some RES (i.e., PV) can be housed with it. Then it supposed to considered as a joint master unit operating in V/f control to serve the predetermined voltage and frequency support to the islanded MG. In such a case, an interrelated V/f and PQ control strategy needed to comprehend the frequency regulations. However, the master-slave control strategy has some crucial disadvantages as many communication channels, required central supervision, higher installation cost, laborious for extensive systems, sensitive to single-point failures. As stated earlier in this control strategy, the grid-forming power converters play vital roles in determining and providing the reference voltage and frequency to the slave DGs in IS mode. These converters are also responsible for the quick handling of load variations and transitions in AC MG.

Helio Antunes *et al.* presented a fault-tolerant configuration formed by grid forming power converters [82]. Hence, it adds robustness to the Master-slave control strategy. The research carried out in literature [83], somewhat able to improve the redundancy of master-slave control by introducing a rotating priority window, giving an arbitrary choice of the master unit. The literature [84] presented automated master-slave control, which makes it a reliable control technique. Research [85] implemented an MG based on controller area network (CAN) and ZigBee types' communication network. First, the master-slave control strategy applied, and it shows acceptable stability and current sharing performance. Second, it adopted a combined master-slave/droop control strategy, and it shows better performance than the first one, but it suffers from the maximum allowable delay bound. The literature [86] adopted the running state of the controller to improve the master-slave control strategy. Here the concept of energy storage inverter phase-locked method resolves the problem of instantaneous alteration of control signals produced by energy-storing inverter controllers during operating mode transition. This method also solves the problems that occur during the development of unplanned faults and removes harmonics content from the AC voltage and current in AC microgrid.

Literature [87] presented an SMC based primary control strategy to speed up the regulation of voltage and frequency of a master-slave controlled AC MG. Here two kinds of SMC proposed, one is current mode control, and the other is voltage mode control. The current mode control is applied to the slave DG units while the voltage mode control enforced to the master DG unit. The results are verified with the PI-based control strategy. The presented result shows better performance compared to that is of the PI-based control strategy of the microgrid. In literature [88], the master-slave control strategy was used to present a Distributed energy resource (DER) management algorithm in a multi-DGs MG. Here, during islanding, the ESS Power converter is considered as a master unit while other DGs are treated as slave units. During ON grid operation, the DGs are regarded as master units and provide reference voltage and frequency support to the PCC. This strategy of DERs management provides satisfactory power quality and transition issues. This DERs management algorithm can supply a higher possible load without compromising with the life span of the battery, fuel cells, power converters, and energy cost. The literature [89] presented a distributed master-slave control strategy for series cascaded MGs to regulate power and voltage generated by the non-dispatchable DGs and enhanced their utilization in the MG.

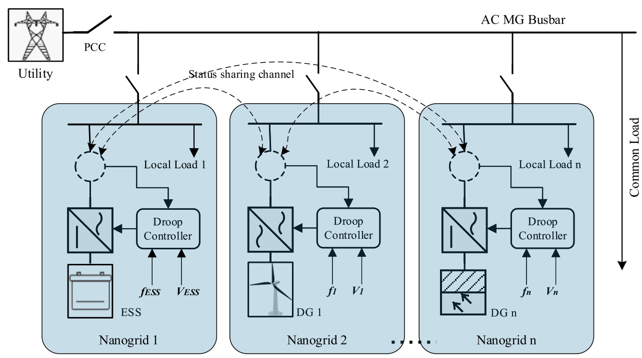

FIGURE 15. Pictorial illustration of P2P control strategy [51].

2) P2P CONTROL STRATEGY

It is an isolated mode of MG control strategy. The pictorial illustration is shown in Fig. 15. In this strategy, the MG is considered to have many nano grids. These nanogrids are consisting of equal DGs and ESS units and local load and a typical load. There is no master-slave relation among these nanogrids, and these are controlled in a decentralized manner. These nanogrids operate on the droop control method to provide support of voltage and frequency to the MG bus-bar and regulate the output power based on local information. However, these nanogrids do not share any information among them except the same status to tackle a typical load as per the availability of the energy resources [80]. As there are no communication channels among these nanogrids, so it saves lots of money in constructing communication lines and reduces its complexity. Any sudden variation in loads effectively can be divided among the DGs and ESS units based on their droop coefficient to keep power balance between generations and consumptions during IS mode of operation. Unlike master-slave control, this control strategy empowers every DG and ESS to take part in automatic power output allocation and promotes the plug and play action of DGs. Concurrently, there is a deviation in the droop control of the DGs and ESS units, despite the operating modes of the AC MG resulting in a smooth transition between the operating modes, i.e., GC to IS or IS to GC [51].

In the practical application of P2P control, still few DGs can use the PQ control to recognize the MPPT and unity p.f operation while other DGs and ESS units depend on droop control to tackle the power-sharing action. Unlike master-slave control, if any fault occurs in the MG, it needs to isolate only the faulty nanogrids, and the rest part of the MG will work satisfactorily. Hence this control strategy is more reliable than the master-slave control strategy. In literature [90], the authors presented a gossip communication-based, fully distributed P2P control strategy. This gossip communication easers the measurement of locally available voltage and current of DGs and allow sharing of measured information of it with neighbour DGs to ensure accurate power-sharing among them. It enables plug and play action of each DGs and robust it against the mall operated transitions. The literature [91], [92] described a distributed secondary control system that ensures accurate power-sharing among the local DGs and enables restoration of voltage and frequency of the MG while isolating a faulty local DG. The research work [80] presented a coordination-based master-slave oriented P2P control strategy, which combines the benefits of both master-slave control and P2P control and results in steady operation before and after the transitions of modes.

Further, the literature [93] presented an angle droop control (ADC)-based P2P control strategy for controlling energy transactions between MGs operating simultaneously in an extensive MG system. The energy transaction control is achieved by introducing the concept of a power router into the inter-linking converters. However, this research work is difficult to implement in current MG scenarios.

3) HIERARCHICAL CONTROL STRATEGY

Hierarchical control uses a robust communication network-based MGCC in order to determine and address control signals to all DGs, ESS units, and controllable loads present in the microgrid based on the collected status information. At first, the MGCC forecast the load demand and availability of power generation in the microgrid to develop final operation plans. Second, it collects the information about the status of voltage, current, and power and adjusts the power output by updating the operation plans in real-time. In this way, it regulates the ON and OFF of DGs, ESS units, and loads. In this fashion, the stability of voltage and frequency is assured, and suitable protection function is maintained for islanded MG. Based on the functionality of the central controller, the Hierarchal control strategy can be classified as; 1. Two-level hierarchical control, and 2. Three-level hierarchical control. The vulnerability of two-level hierarchical control can be increased by adopting the control architecture set out in the literature [94]. This control architecture requires a weak communication network for mutual communication among the DGs, ESS, controllable loads, and higher-level controller. Due to the distribution of control authorization between main control and central controller, the system will remain in operation during short-time communication failure due to faults. Three-level hierarchical control [95], [96] is usually designed for an extensive AC/DC MG system consisting of a group of MGs. Fig. 16 illustrates the control architecture of a three-level hierarchical control.

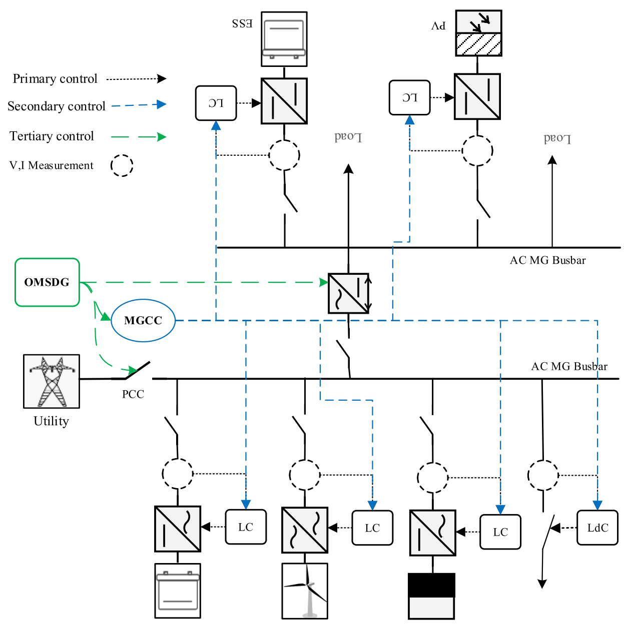

FIGURE 16. Illustration of three-level hierarchical strategy in AC/DC MG.

The different levels are;

Primary control: responsible for the decent operation of all DGs, ESS units, and load controllers (L_dC) in order to ensure power quality and transient power balance for sensitive loads.

Secondary control: it uses a central controller to optimize the economical operation of each MG. It establishes communication with users to deliver/aware of their needs/current power scenario in the grid.

Tertiary control: it responsible for maintaining the stability, power flow control, ancillary services, and security of the entire system.

Some researchers [97], [98] divided the tertiary control into two sub-levels based on its functionality and presented as four-level hierarchical control. The literature [99] showed a fully distributed two-level hierarchy control. The proposed secondary control can be derived by crossing over any barrier between conventional secondary and tertiary control. Literature [100] presented a time-scale based hierarchy control strategy to enhance power sharing and power quality of AC MG. This research proposed two-time scales. The first one is the short-time scale, which uses substantial droop gain to enhance power-sharing. The second one is the large-time scale, which is responsible for adjusting the set-point of no-load droop characteristics (i.e., V and f) in order to enhance the power quality. Literature [101], introduced a reliable control strategy for the IPC of an AC/DC MG operated on hierarchical control. This strategy makes the IPCs multifunctional and eliminates the adverse effects of inaccurate or slower mode switching. It is hence improving the reliability and flexibility of hierarchically controlled AC/DC MG.

Literature [102] presented distributed hierarchy control for AC MG operating in any mode of operation (i.e., GC, IS, and transition mode). In this, the primary control is achieved by the essential droop control. Secondary control accomplished by distributed control based on leader-follower consensus protocol and tertiary control obtained by a mode-supervisory control. This control frame-work ensured the i). V/f restoration and accurate power-sharing in IS mode. ii) Flexibility in power-flow regulation between the utility grid and MG in GC mode. iii) Extensive control for smooth transition from GC to IS mode and vis-versa. Thus, this control strategy can be applied to all four operating modes of MG.

The research work [103] presented a hierarchical strategy for a 3-phase 4-wire islanded AC MG and enhances the operational stability under unbalanced and non-linear load conditions by accomplishing precise active and reactive power-sharing with zero reactive power-sharing error. The literature [104] presented the applicability of a two-level Hierarchical control strategy to optimize the power flow in an islanded AC MG. Where the primary control performed by adopting conventional droop control responsible for regulating voltage and frequency while the secondary control took a centralized extended optimal power flow (EOPF) control accountable for the management of active and reactive power sharing among the DGs. Literature [105] extended the hierarchical control strategy to switch the power converters fed to the DERs in VSI or CSI mode according to the requirement in the Bus-bar before and after the contingency conditions in the AC MG.

4) MULTI-AGENT CONTROL STRATEGY

This control strategy involves a MAS composed of multiple autonomous intelligent agents possessing local wisdom with limited abilities and capable of interacting together in an environment in order to achieve a specific objective or task [106]. The environment could be anything (i.e., hardware, software, or system) to the agent. An agent can be treated as an intelligent entity, performing in an environment

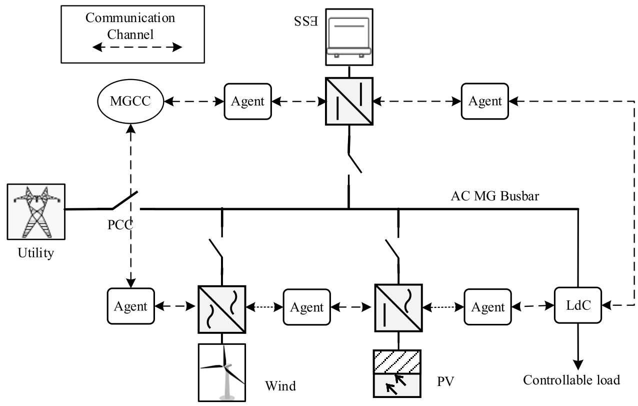

FIGURE 17. Illustration of MAS based control in AC MG.

with a degree of autonomy to achieve a specific objective or goal. An agent can act automatically in response to the environment changes and can take some actions to change the environment. Here the word 'autonomy' implies that an agent is capable of executing its task without the direct intervention of humans. As we know, the microgrid is a system which has different levels of entities, and they could be some time seller or buyer. So, in this market scenario, the MAS technology assumes a significant job in power management [107], [108], resource allocation, and scheduling [109], controls, and optimizing [110] the microgrid. Fig.17 illustrated a control strategy based on MAS technology. A detailed review of MAS based control strategies in MG up to date 2014 has been presented in the literature [111]. Likewise, in other control strategies, this control scheme requires a communication system to establish interaction among agents and micro-terminals in the operating environment. The research works presented in the literature [107], [112] adopted the MAS based control algorithms to increase the robustness of MGs against communication failures. In these researches, each ESS unit considered as an agent with the autonomy of balancing the SoC during charging and discharging. The literature [113] presented a MAS based adaptive control strategy, validating the stability and robustness against faults in the IS/GC mode of AC/DC MG.

5) MODERN PREDICTIVE CONTROL STRATEGY

Due to intermittent and unpredictable behaviour of RES based DGs and uncertainty in load variations, it is still challenging to balance the demand power and generated power in an AC MG. So, there is always a problem of balancing power-sharing among DGs and ESS units. Many researchers presented an MPC-based control strategy to provide the solution to this problem while optimizing the DGs. Literature [114] presented an MPC-based supervisory control strategy to optimize and cope with the uncertainty of RES generators in an AC/DC MG. Here the sensitivities of AC and DC MG Bus have been utilized to predict the voltage magnitude and frequency accurately. Its presented

TABLE 2. Summary of recently developed power converter control strategies of MG.

Converter Control strategies		Presented solutions	Possible Problems
In the case of DC sub-grid	[38]	Mitigated the effect of CPLs in DC sub-grid Maintain constant voltage and stability at DC busbar irrespective of charging/discharging phenomena of ESSs Robust and efficient control	The chattering effect caused by SMC not studied
	[39]	Mitigated the effect of CPLs in DC sub-grid Maintain constant voltage and large-scale stability at DC busbar Ensures robust control	The chattering effect caused by SMC not studied Response reduces as the no. of CPLs increases in the busbar
	[40]	Robust against uncertain CPLs Maintain voltage control and stability Faster dynamic response	Complicated designing of voltage controller
	[41]	Provides constant power output from the RES to the DC busbar Fast dynamic response to power fluctuation	The study limited to only PV based DC MG
	[42]	Provides constant current during voltage sag in the DC busbar Capable of fault ride through Fast output power recovery just after the voltage sag	The study limited to only PV based DC MG
	[46]	Proper voltage regulation under DC droop control Allow plug and play feature Enhanced stability	Complicated to implement due to the involvement of the communication channel
	[47]	Reliability of ESS units enhances Equalize the load current sharing between the ESS units and DC busbar	Limited performance Under optimum control, it provides unequal current sharing
	[48]	Mitigate the effect of unequal terminal voltages of DGs Effective voltage regulation and power-sharing in the DC busbar Enhances power-sharing among the DGs Improves the reliability, stability, and flexibility of the DC busbar No communication required	Causes unnecessary curtailment of RESs and reduces the storing capacity of the ESS units
	[49]	Effect of line parameters mitigated The circulating current between parallel DGs suppressed Power-sharing accuracy improved	Slow dynamic response to load variations in the DC busbar
	[50]	Current-sharing accuracy improved Immune to communication failures	Indulge complex circuitry due to the use of the concept of virtual frequency in the droop controller
In the case of AC sub-grid	[53]	Comparative analysis of Optimization techniques, i.e., GA, PSO, PSOd and ABC Improve the utilization of ESS units Reduces the power stress on the sub-grids	Voltage and frequency stability issues
	[54]	Efficient performance Enhances the utilization of DGs Stable under various solar irradiation conditions	Moderate to implement The utilization of AC side DGs not studied
	[55]	Accurate reactive power-sharing among DGs Reduces the effect of high droop gain	Moderate to implement Voltage magnitude may vary
	[56]	Improves dynamic stability Optimizes the system performance	Moderate to implement
	[57]	Improves reactive power-sharing Minimizes voltage magnitude variations	Limited to the radial network only Moderate to implement
	[58]	Improves reactive power-sharing among DGs Immune to communication delay or failure Allow Plug-and-play operation	Complex to implement Costly due to communication network It becomes complicated as no. of DGs increases
	[59]	Equalizes thermal-sharing among the power converters Improves the reliability of MG	Complex to apply Poor reactive power-sharing due to uses of basic droop control
	[60]	Accurate the power-sharing among ESS units based on their SOC	Complex to implement RES based DGs not taken into consideration
	[61]	Eliminates the effect of the capacity of ESS units in power-sharing	Moderate to implement May frequency deviate during SoC balancing
	[62]	Proportional power-sharing among the DGs Robust against start-up transients	It becomes complicated as no. of DGs increases Load dynamics in control operation not included
	[63]	balancing power-sharing among the DGs and also valid for no-economical operation Optimizes power-sharing among the DGs Active power losses minimization Minimizes power losses	Moderate to implement Complicated control architecture due to mixed optimization

TABLE 2. *(Continued.)* **Summary of recently developed power converter control strategies of MG.**

	[64]	Regulates bus voltages feeding different loads Accurate active and reactive power sharing among the DGs Reduces the effect of line impedance Reduces circulating current between parallel DGs	There is a trade-off between the control objectives and performances of the strategy
	[65]	Quickly responses to load variations Good overall performance Eliminates V & f deviations	Difficult to apply in an extensive system Challenging to achieve Global power loss minimization Equal charging/discharging cycles may affect the performance
	[66]	Fast power-sharing during the steady-state and transient performance No communication channels required	Complex to implement Less robust to load variations
	[67]	Improves overall operational efficiency No communication required	Moderate to implement Difficult to apply an extensive system
In the case of IPC	[69]	Accuracy in power flow control between sub-grids Maintain the stability of the AC/DC MG Enhances power quality	Circuitry becomes complex due to power quality controller
	[70]	Accurate power flow control with improved stability Faster dynamic response Robust against transients	The effect of high-frequency oscillations may exist
	[71]	Improves power quality Proportional power-sharing between AC & DC MG	Complex to implement Spikes in V & f at AC busbar
	[72]	Regulates voltage and frequency locally Improves power-sharing between AC and DC MG Improves reactive power-sharing between AC MG and IPC	Complex to implement Limited to radial connected DGs
	[73]	Improves small-signal stability Proportional power-sharing between AC and DC MG Allow plug and play feature	Moderate to implement Communication delay may affect the performance
	[74]	Do not require communication channels Communication free operating cost minimization of AC/DC MG	Complex to implement Deviation in reactive power-sharing at AC bus
	[75]	Improves power-sharing between AC & DC MG Stable operation of AC/DC MG	Easy to implement Less robust to load variations
	[76]	Improves power quality Provides economic power-sharing among the DGs Eliminates V & f deviations caused during	Complex to implement The generation cost of individual RES not taken into consideration

result ensures the increase in RES penetration with economic generation in AC/DC MG.

Further, the literature [115] presented an MPC strategy without employing any PID controller to stabilize the AC voltage output of power converters and to regulate the power-sharing among the DGs in an AC MG. A similar concept has been described in the literature [116] for AC/DC interlinking converters used in AC/DC MG. The research [117] presented MPC based control strategy for the power converters of the AC MG to provide robustness in power-sharing among the power converters operating either in steady-state or transient state.

The literature [118] introduced a convex MPC based control strategy to optimize the dynamic power flow among the ESS units scattered in the AC MG. This strategy provides similar performance compared to a non-convex based optimization strategy. However, it reduces the required computing time by a factor of 1000, which makes it suitable for real-time usage of the MPC technique. The research work [119] presented a distributed MPC-based hierarchical control strategy to control and resolve the power quality and load sharing issues in an islanded MG. The primary control adopted a virtual impedance loop and a droop controller and responsible for regulating power-flow and power-sharing among DGs and ESS units. The secondary control accountable for adjusting the frequency and terminal voltage up to the assigned limit in the islanded MG.

6) OTHER CONTROL STRATEGIES

Apart from the above-discussed control strategies of AC/DC MG, there are several control strategies like fuzzy control, neuron control, IoT based control, etc. However, these other control strategies also focus on the Decentralized control scheme to overcome the drawbacks of the Centralized control scheme. IoT based control scheme provides wireless communication among the entities of AC/DC MG. IoT networks enable smart sensing, measuring, and monitoring of power flow among the sub-grids and main grids, which further takes MG towards the concept of the smart microgrid. The fuzzy logic control and neuron control mainly employed with various optimization techniques (GA, PSO, PSOd, ABC, etc.) to design and fine-tuning of PI controllers in energy management systems of MGs.

TABLE 3. **Comparative summary of recently developed control strategies of MG.**

MG Control strategy		Control architecture adopted	PC/local control strategy adopted	V & f regulation	Power-sharing management	Performance Optimization	Stability	Energy management	Implementation complexity
Master-slave	[80]	H	PQ & Droop control	Y	Y	X	Y	X	Complex
	[81]	C	Droop Control	Y	Y	X	X	X	Moderate
	[85]	C	Droop control	X	Y	X	Y	X	Complex
	[86]	C	PQ & V/f control	Y	Y	X	Y	X	Moderate
	[87]	C	PQ & V/f control	Y	Y	X	X	X	Moderate
	[88]	C	V, I Control	Y	X	X	Y	Y	Complex
P2P	[90]	D	Droop control	Y	Y	X	X	X	Moderate
	[92]	H	Droop control	Y	Y	X	Y	X	Easy
	[93]	H	Angle droop control	X	X	X	X	Y	Complex
Hierarchical	[95]	H	Droop control	Y	X	Y	X	X	Complex
	[96]	H	V/f control	Y	Y	Y	X	X	Moderate
	[99]	D	SMC-based Droop	Y	Y	Y	Y	X	Complex
	[100]	C	Droop control	Y	Y	X	X	X	Complex
	[101]	C/D	Droop control	Y	Y	X	Y	X	Moderate
	[102]	H	Droop control	Y	Y	X	Y	X	Moderate
	[103]	C	Droop control	Y	Y	X	Y	X	Moderate
	[104]	C	Droop control	Y	Y	Y	Y	X	Moderate
	[105]	C	Adaptive-based droop control	Y	X	X	Y	X	Complex
Multiagent	[106]	H	X	X	X	X	X	Y	Complex
	[107]	D	X	Y	Y	Y	X	Y	Complex
	[108]	D	X	Y	X	Y	Y	Y	Complex
	[111]	C/D	X	Y	Y	Y	X	X	Moderate
	[113]	X	Droop & f-scheduling control	Y	X	X	Y	X	Complex
MPC	[114]	X	X	X	X	X	Y	X	Moderate
	[115]	X	Droop & MPPT based control	Y	Y	Y	X	X	Moderate
	[116]	X	Droop control	Y	Y	X	Y	X	Moderate
	[118]	D	Droop control	Y	Y	X	Y	X	Complex
	[119]	X	Droop control	X	Y	Y	X	X	Moderate

Where; C: Centralized control, D: Decentralized control, H: Distributed control and X: Not discussed, Y: Yes discussed and rectified

IV. COMPARATIVE ANALYSIS

In table-2, a comparative summary presented for the newly developed power converter control strategies of AC/DC MG based on offered solutions and possible problems. These potential problems are not the same, varies case to case. One more comparative analysis is presented in table-III based on the issues discussed and rectified in newly developed control strategies of AC/DC MG by different researchers. Where 'Y' indicates that the problem is addressed and rectified, and 'X' means that the problem not discussed or rectified. Further 'C,' 'D,' and 'H' indicates the adopted control architecture Centralized, Decentralized and Distributed Control architecture respectively. The implementation complexity is classified based on the complexity of the communication network and adopted Microgrid control strategy; 'Complex' indicates the MG indulging high bandwidth communication network, mixed type MG control strategy. 'Moderate' means the MG is indulging low bandwidth communication networks with a single MG control strategy. 'Easy' indicates the MG indulging local communication network with an only control strategy. This table helps us to understand how the performance of the MG may vary due to the chosen control strategy, and some of the critical issues left unsolved.

V. CONCLUSION AND FUTURE CHALLENGES

In this article, we presented an overview oriented state-of-the-art on the power converters control, and Control strategies of AC/DC MG. Tables 2 and 3 may help us to formulate significant challenges, i.e., V & f regulations, accurate load-sharing to avoid overloading and stability problems, DG coordination, cost-optimization, power flow control, and power generation & demand forecasting that could not be resolved permanently in AC / DC MG. These challenges can be addressed globally, i.e., MG Control as well as locally, i.e., power converters control. Some research [113]–[116], [119], which are mainly focused on a control strategy based on MAS or MPC, indicate that the challenges mentioned above can be addressed through the control of power converters without the use of any MG control architectures.

The analysis of our literature survey reveals that most of the research works concentrated on the droop control to eliminates its disadvantages. Fewer research works have been done on the PQ control and the V/f control. The PQ control and the V/f control mainly suffering from delaying response to load variations in the MG, which creates sever stability, power quality, and load sharing issues. So, there is a possibility to improve the PQ control and the V/f control strategy of power converters control or local control.

Simultaneously, our literature survey reveals that most of the research work carried out on the global control (HC, M-S, P2P, MAS, and MPC) strategies but did not able to rectify all the significant challenges and issues completely. Because of the presence of the IPCs and the defer in the local control strategies. So, still, we need to work on the Future through capabilities [120] to immune the stability of the system against rising no. of low inertia micro-sources, Complexity due to communication channels, Security challenges due to the popularity of wireless-communication based control strategy. Then we can answer partially to the question 'what kind of control strategy to be guaranteed?' for an AC/DC MG.

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SHAMSHER ANSARI received the bachelor's degree in electrical and electronics engineering and the master's degree in power electronics and electric drives from Jawaharlal Nehru Technological University Hyderabad, India, in 2011 and 2013, respectively. He is currently pursuing the Ph.D. degree in electrical engineering with Dr. A.P.J. Abdul Kalam Technical University, Lucknow, under the Homi Bhabha Research Cum Teaching Fellowship Scheme. He worked as an Assistant Professor with the Electrical Engineering Department, IEC College of Engineering and Technology, Greater Noida. He is also working as a Research Scholar with the Rajkiya Engineering College, Mainpuri, India. His research interests include power converters control and control strategies in microgrid.

ASEEM CHANDEL (Senior Member, IEEE) received the bachelor's and master's degrees in electrical engineering from Uttar Pradesh Technical University, Lucknow, in 2002 and 2009, respectively, and the Ph.D. degree in DER planning from Uttarakhand Technical University, Dehradun, India. He is currently an Associate Professor of electrical engineering and the Director (Offg.) with the Rajkiya Engineering College, Mainpuri, and a Convener of the SAC IEEE UP Section. He is having almost 18 years of academic experience in various technical institutions. He has worked in Asia's first hydropower institute (THDC Institute of Hydropower Engineering and Technology and Tehri Constituent Institute, Uttarakhand Technical University). His research interests include power system restructuring, distributed generation, smart grid, green energy, and environment. He is a Senior Member of IEEE-PES and IEEE-WIE. He has been a member of the IEEE-R10 Student Activity Committee and a Professional Activity Convener (PAC) of the 2019 IEEE UP Section.

MOHD TARIQ (Senior Member, IEEE) received the bachelor's degree in electrical engineering from Aligarh Muslim University, Aligarh, the master's degree in machine drives and power electronics from the Indian Institute of Technology (IIT)-Kharagpur, and the Ph.D. degree in electrical engineering with a focus on power electronics and control from Nanyang Technological University (NTU), Singapore.

He has worked as a Researcher with the Rolls-Royce-NTU Corporate Laboratory, Singapore, where he has worked on the design and development of power converters for more electric aircraft. Before joining his Ph.D. degree, he has worked as a Scientist with the National Institute of Ocean Technology, Chennai, under the Ministry of Earth Sciences, Government of India, where he has worked on the design and development of BLDC motors for the underwater remotely operated vehicle application. He is currently working as an Assistant Professor with Aligarh Muslim University, where he is directing various sponsored research projects and leading a team of multiple researchers in the domain of power converters, energy storage devices, and their optimal control for electrified transportation and renewable energy application. He also served as an Assistant Professor for the Maulana Azad National Institute of Technology (MANIT), Bhopal, India. He has authored more than 130 research papers in international journals/conferences, including many articles in IEEE Transactions/journals. He is also the inventor of 17 patents granted/published by the patent office, India.

Dr. Tariq was a recipient of the 2019 Premium Award for the Best Paper in *IET Electrical Systems in Transportation* journal for his work on more electric aircraft and also the Best Paper Award from the IEEE Industry Applications Society's (IAS) and the Industrial Electronic Society (IES), Malaysia Section—Annual Symposium (ISCAIE-2016) held in Penang, Malaysia. He is a Young Scientist Scheme Awardee supported by the Department of Science and Technology, Government of India and also a Young Engineer Awardee by the Institution of Engineers (India). He is also the Founder Chair of the IEEE AMU SB and the IEEE SIGHT AMU.