Comprehensive Review on the Strategies for Controlling the Interconnection of AC and DC Microgrids

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Abstract: The interconnection of AC and DC microgrids results in a hybrid AC/DC microgrid (HMG). In light of HMGs, the future smart grid implementation will be facilitated. One important aspect in HMGs is the interconnection of AC and DC microgrids and control of bidirectional interlink power converters (BILPCs), which has taken a lot of research attention in the last decade. The BILPCs are the most prevalent method for interconnection of HMGs. Thus, the current study first reviews different interconnection methods and control challenges of AC and DC microgrids in HMGs and then overviews various control strategies of BILPCs presented in literature, all carried out in a comprehensive manner.

Keywords: Hybrid microgrid, converter control, interconnection, interlink bidirectional power converter

1. Introduction

Renewable energy sources (RESs), such as wind energy and photovoltaic (PV) etc., have dramatically emerged in power systems during past two decades, as a result of many researches as well as industrial efforts throughout the world [1-3]. The main goal to embed these resources in power systems were the climate changes, ever-increasing energy demand, reliability and security of power supply etc. These issues motivated many researchers and industrialists to provide a near modular setting for development and integration of RESs in power systems in the format of microgrids [4, 5]. Therefore, in framework of microgrids, the RESs can easily be managed, controlled, and integrated in power systems. From operational viewpoint, and of course not need to mention more details, each microgrid can operate in standalone/islanded/grid-forming mode, or grid-connected/following mode, as used in smart grid terminology [6, 7].

Until now, three types of microgrids have been familiarized to the professionalisms: 1) AC microgrids, 2) DC microgrids, and 3) hybrid AC/DC microgrids. The first two types have been well-investigated in literature. The AC microgrids include mainly AC sources and loads. There is a common AC bus which all loads and sources are connected to it. On the other hand, in a DC microgrid the major part of sources and loads are DC. Similarly, a common DC bus exists to which all sources and load are connected to. In both AC and DC microgrids, if there is a load/source which can't be connected to the common bus directly, for example, a DC load in an AC microgrid, the DC/AC power converters are used as interface. The third type of microgrids, i.e. the hybrid AC/DC microgrids, have gotten more attention in literature during past five years. As reported, these microgrids will the mainly used structure in upcoming smart grids since these microgrids smooth the realization of future grids by providing easily add-in and plug-and-play features for RESs [8-10].

These microgrids actually consist of interconnection of both AC and DC microgrids as an independent body. That is to say that these microgrids enjoy all blessings of both AC and DC microgrids simultaneously. The hybrid AC/DC microgrids have been classified to three types: 1) hybrid AC/DC microgrids with AC coupling, 2) hybrid AC/DC microgrids with DC coupling, and 3) hybrid AC/DC microgrids with AC and DC couplings. The first type actually is a special type of AC microgrid in which there are a considerable number of DC loads. These loads are connected to the common AC coupling bus via interface DC/AC power converters (IPCs) [11, 12]. In contrasts, the second type is a certain type of DC microgrid in which the number of AC loads is noticeable. These loads are connected to the common DC coupling bus through interface AC/DC power converters. The third type, i.e. the hybrid AC/DC microgrids with AC and DC couplings, is in the scope of this paper. As its name implies, there are two coupling buses in these microgrids; the AC and DC common buses. In fact, this microgrid consists of the first two hybrid microgrids, commonly interconnected by BILPCs. This interconnection can be provided by a single BIPC or multiple BILPCs, i.e. parallel-connected BILPCs. To control these BILPCs, different approaches and strategies have been presented in literature [7, 13, 14].

The main purpose of the current paper is to review and classify the control strategies of BILPCs. Besides, instead of using BILPCs, other alternatives have been described in recent researches which are also reviewed in this work. One should notice that we have distinguished between two technical terms here. We referred to “BILPC” to those power converters which are connected between two AC and DC links in the hybrid AC/DC microgrids with AC and DC couplings. The review of different control strategies of these called “interlink” power converters is the main focus of this work. By contrast, we referred to “IPC” to those power converters which act as interface between a distributed generation (DG)/load and a common DC or AC bus. The control strategies of these called “interface” power converters are out of scope of this work. Therefore, this review excludes the “microgrid control” and dedicates to BILPCs control only.

Different review works have been accomplished by many researchers in the field of microgrid topologies and control strategies. In [15], demonstrative research projects on microgrids have been described. These include projects around the U.S and EU, Asia and Canada. Furthermore, the main development barriers and control challenges have been discussed. The authors in [16] have reviewed microgrids, which have been successfully implemented and experimentally tested. These microgrids have been installed, for example, in University of Manchester, Hefei University of Technology etc. The control systems and elements of these microgrids have been verified and reviewed. The main feature of this study was that it has summarized these testbench microgrids which makes it a straight clue for readers to have a quick comparison of real microgrid cases.

In [17], a general review on microgrids control strategies has been presented where the authors have described the control hierarchy in microgrids. Mainly, three control levels have been discussed: primary, secondary, and tertiary. Different strategies for each control level have been described and the control challenges have also been debated. In [18], a survey on control of AC microgrids has been accomplished. The authors have discussed different control aspects including internal control loops, and primary and secondary control levels. The V-f and P-Q controls in AC microgrids have been reviewed. In a similar way for DC microgrids, a review on their control strategies has more recently been published in [19], where different topologies of DC microgrids including multiple nano-grids, and multi-terminal/bus/ladder-bus DC microgrid have been considered.

Also, the droop control methods mainly for storage systems have been reviewed and a typical process of an has been illustrated algorithm for determining the optimal sizing of storage systems and RESs. Likewise, in [20] a supervisory view has been taken to analyze different control scheme of DC microgrids. The virtual impedance-based and nonlinear droop control methods have taken a special attention in this review. Also, the authors have presented various active power and current sharing methods which have commonly been used in literature. Furthermore, the economic dispatch and unit commitment for microgrids have been described based on agent concept. The authors in [21] have presented an overview on microgrids with provision of reserve management and demand response. Different control strategies including both standalone and grid-connected operation modes, have been reviewed by giving special attention to primary reserve. Then again, droop-based primary control including *V-f* and *P-Q* controls have been revisited there.

In [22], the key drivers and motivations for developing microgrids have been discussed; coupled with a look into control strategies and challenges. The market structure and policies for microgrids have been discussed, too. In [23], a survey on droop control strategies of microgrids has been presented. This includes traditional, virtual impedance loop-based, and adaptive droop controls. Furthermore, a brief survey of control and energy management of microgrids has been described in [24], where communication-based and centralized energy management schemes have been analyzed. Also, a review on power management schemes in HMGs has been presented; some installed HMGs have been discussed in different countries and control strategies for AC, DC, and AC/DC coupled HMGs.

Keeping in mind that the current paper deals with reviewing control strategies of BILPCs and interconnection methods of hybrid AC/DC microgrids, it should be mentioned that there are also some review papers regarding, for example, overviewing different topologies and control of HMGs. But those review papers are different from the current study. In [25], different configurations of HMGs have been distinguished. The authors have presented the typical characteristics of each structure of AC coupled and decoupled HMGs.

The same authors in [26] have classified and reviewed different control strategies of HMGs. The hierarchical control strategy of HMGs has been considered and the microgrid operation modes, including grid-forming and grid-following, have been discussed. In [27], different protection schemes for HMGs have been overviewed, coupled with a critical protection analysis. The authors in [28] have reviewed some droop control methods for interlink power converters in HMGs. These methods include conventional, piecewise, standard, and bilateral droop controls. More recently, an overview on interlinking power converters has been presented in [29], where the task of these converter has been clarified in primary regulation of microgrids. What's more, different topologies of these power converters have been identified and explained. It is important to note that the work by [29] is a general study on interlink power converters; including DC/DC, AC/AC, and AC/DC power converters in AC, DC, and AC/DC microgrids and little attention has been given to BILPCs.

In view of future smart grids, the BILPCs play important roles and accomplish different tasks as follows:

- Instead of applying passive element-based interconnections, i.e., traditional RL distribution lines, the power converter-based interconnections, for example, using BILPCs, will be a common method for connecting different microgrids because passive elements bring many limitations, for instance, in voltage control and stability maneuvering etc. [30, 31].

- By implementation of BILPCs, the microgrids with different characteristics can be interconnected. This interconnection via BILPCs brings more degree of freedom for active and reactive power flow control between the AC and DC microgrids.
- BILPCs-based interconnections facilitate the integration of RESs and microgrids in conventional grid [32, 33].
- Through interconnecting the AC and DC microgrids using BILPCs, the capacity of each microgrid is enhanced by providing power exchange feature. This results in postponing investment in adding new energy resources or increasing the energy storage systems (ESSs) capacity.
- Since the RESs are not dispatchable easily, these interconnections result in better utilization of these RESs [34].
- The utilization of the ESSs capacity and also their sizing can be optimized [32, 35].
- The microgrids security and reliability are enhanced [2].
- In passive-based connections, during the line impedance effects, the power system and microgrids stability was endangered. However, the output impedance of BILPCs can be controlled in control loops and the system stability as a whole sustained [2, 36].
- The synergy and cooperation between AC and DC microgrids with power system can be managed by the BILPCs. This results in a lower system complexity and straighter control duties [37, 38].
- The BILPCs can participate in ancillary services, for example, power quality market etc. [36, 39].

Therefore, the BILPCs control scheme is an important problem which has been addressed in tens of research studies and thus, is spotlighted in this paper. To the authors' best knowledge, there is not a review work in which special attention has been given to control of these BILPCs and interconnection of AC and DC microgrids by other alternative methods. The main contributions of the current paper are as follows:

- Different methods for interconnecting of AC and DC microgrids in HMGs are identified. This includes not only the BILPCs, but also other small-scale FACTS-based interconnecting methods; consisting of unified interphase power controller (UIPC), unified power quality conditioner (UPQC), and unified power flow controller (UPFC) which have been proposed in literature.
- Also, other topologies including solid-state transformer and energy router-based interconnecting methods are described as well.
- Control strategies for BILPCs in HMGs are classified and reviewed.

The rest of paper is set-up as follows: Section 2 classifies different interconnection methods of HMGs and related control challenges. This section also describes the various topologies of BILPCs used in HMGs. Section 3 classifies and overviews the control methods of BILPCs. The conclusion is drawn in the last section.

2. Control Challenges and Classification of Interconnection Methods of AC and DC microgrids in HMs

As explained in the previous section, an HMG includes at least one AC microgrid and one DC microgrid which are interconnected together to exchange active and reactive power. The purpose of this section is to classify different methods which have been used to interconnect AC and DC microgrids. The control challenges of each interconnection method are also discussed.

Investigating the literature, the AC and DC microgrids have been interconnected based on one of the following methods: 1) a single BILPC, 2) parallel-connected BILPCs, 3) energy router (ER), 4) solid-state transformer (SST), and 5) small-scale FACTS devices. The brainstorming-based classification is illustrated in Fig. 1. Commonly, the single and parallel-connected BILPCs have been used to interconnected multiple AC and DC microgrids. However, by exploring more in literature, one can find other alternatives. For example, some researchers have proposed ETs and SSTs. Moreover, newly published papers in this area have proposed some novel and modified FACTS devices, specifically, the UIPC, to interconnect an HMG. A descriptive table with some important references according to the proposed brainstorming classification of Fig. 1 is given in Table 1.

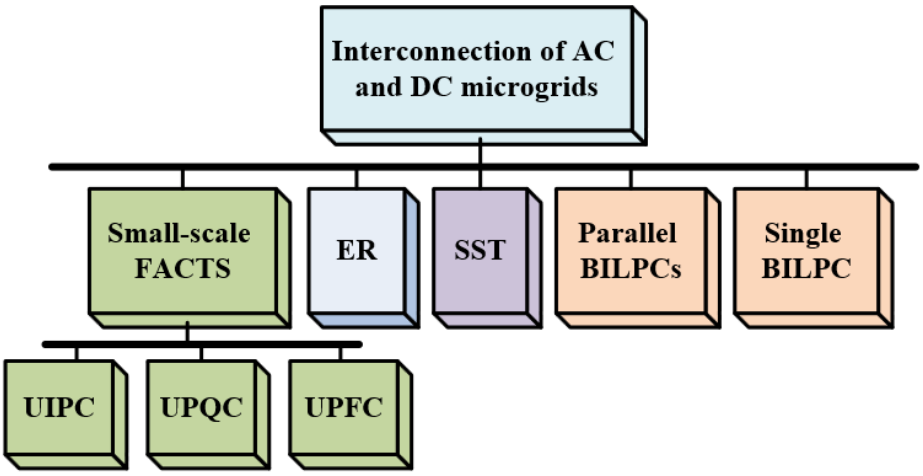


Fig. 1. Brainstorming-based classification of interconnection methods of AC and DC microgrids in HMGs

Table 1. Some important references according to classification of Fig.1

Single BILPC	A single BILPC with various structure have been used to interconnect AC and DC microgrids. However, the amount of transferred power is limited and the reliability is low. [40], [41],[42]
Parallel BILPCs	Several BILPCs are connected in parallel to increase the transferred power and reliability. Different control strategies have been proposed to improve the parallel operation performance. [39], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75]
SST	An SST is used to interconnect AC and DC microgrids. This method provides more degree of freedom in power transfer performance. [76], [77], [78], [79]
ER	The ER consists of various DC/DC and DC/AC power conversion units and is able to interconnect several AC and DC microgrids. [80], [81]
Small-scale FACTS	UPFC, UPQC, and UIPC have been implemented as effective tools to interconnect HMGs. They ad flexibility in power flow and microgrid interconnection. [82], [83], [84]

2.1.Interconnection of HMGs using single BILPC

The three-phase BILPC has been used to interconnect AC and DC microgrids in HMGs. Such a structure is illustrated in Fig. 2 and has been studied in many papers. The AC microgrid may contain wind turbine, diesel generator, microturbine, and various AC loads. On the other hand, the DC microgrid may contain PV, floating PV, batteries, and different DC loads. For the most part, the single-and three-phase full-bridge topologies have been used. Of late, a novel topology for a BILPC which interconnects an HMGs has been presented in [40]. This structure is illustrated in Fig. 3. As shown, such a topology enables HMGs and BILPC to easily accommodate an ESS. The proposed BILPC is a three-port configuration which provides an interconnection between AC, DC, and ESS. This structure has made the DC side fault-tolerant, stable and more reliable. In [41], as shown in Fig. 4, a Γ-Z-Source BILPC (Γ-Z-SBILPC) has been proposed to interconnect AC and DC microgrids in an HMG. The voltage high gain of this topology has resulted in higher efficiency and reliability in comparison to the conventional BILPCs. The HMG has operated in islanded mode and the Γ-Z-SBILPC along with the AC microgrid have been responsible for voltage and frequency control of the islanded HMG. The DC microgrid has been interconnected by a multi-port power converter to reduce the conversion levels and overall cost. The author in [42] has presented a back-to-back structure using single BILPCs to interconnect an HMG. The proposed structure interconnects one AC microgrid to the main AC power grid, as shown in Fig. 5. The DC link is coupled with the common DC bus of a DC microgrid wherein there are fuel cell and PV systems. This topology has facilitated the power exchange control between the AC and DC subsystems with stable operation of DC link.

The most challenging control problems for a single BILPC in an HMG are as follows:

- The AC and DC microgrids are basically different in dynamic characteristics, i.e., the frequency, voltage, phase, and power oscillations. The AC microgrids may also have different characteristics. For example, they may operate in different frequency, phase or voltage levels. This is also probable about the DC microgrids. The DC microgrids may operate with different output voltage levels etc. Therefore, the plant is time-varying or nonlinear [43, 85].
- In each microgrid, there are some nonlinear phenomena and disturbances which affect the exchanged power. For example, the harmonics in an AC microgrid, resulted from nonlinear loads etc., result in voltage fluctuation and phase deviation which must be considered during control system design [86, 87].
- The HMGs include many uncertainties; both parametric and unstructured uncertainties. This is due to the fact that there are various DGs whose output power are fluctuating. Also, there are unforeseen changes in the loads and system parameters. Reducing the effects of the system uncertainties and disturbances on the closed-loop system stability and output response, is crucial for a single BILPC to have a stable operation and present flexible power exchange capability [44, 88].
- The duty cycle of the BILPC may include some uncertain parts. This causes change in output voltage variation which must be addressed well [13, 89].
- The size of the output LC filter should be minimized as much as possible. The size of this filter is directly related to the electromagnetic and electrostatic energies stored in inductance and capacitance of the LC filter, respectively. These stored energies are also in relation with the output voltage and current of the BILPC. Therefore, assigning appropriate reference values and tracking capability are essential tasks for a well-designed control system to optimize the filter size and reduce the costs, as mentioned in [45].

- In grid-following mode, the BILPC usually acts in power control mode. Therefore, the main rule of the control system is to adjust the assigned reference values to the exchanged active and reactive power to/from the main power grid or between the interconnected microgrids. In the islanding mode, however, the control system is expected to do different tasks. In this operation mode, the BILPC is responsible for the regulation of the voltage and frequency in the AC microgrid and the DC bus voltage in the DC microgrid. Moreover, some researchers have removed ESSs in the AC microgrids by delegating the tasks of ESSs to the BILPC. Therefore, the control system should be sophisticated to handle such tasks [90, 91].
- The stability of the DC link is an important issue which should be addressed. Since the DC link is connected to a DC microgrid wherein there are some DGs with variable output, for example, PV systems, the DC link voltage may fluctuate which results in oscillation in exchanged power and instability. For the AC link, this problem may exist, but the major concern is with DC side as described in [92]. All in all, the stability of these links, especially the DC voltage, is commonly handled by the control system [33, 93].

Thus, these challenges should be addressed when designing a control strategy for a BILPC located in an HMG. In the literature, there are different control strategies presented to address these tasks and will be overviewed in the next section.

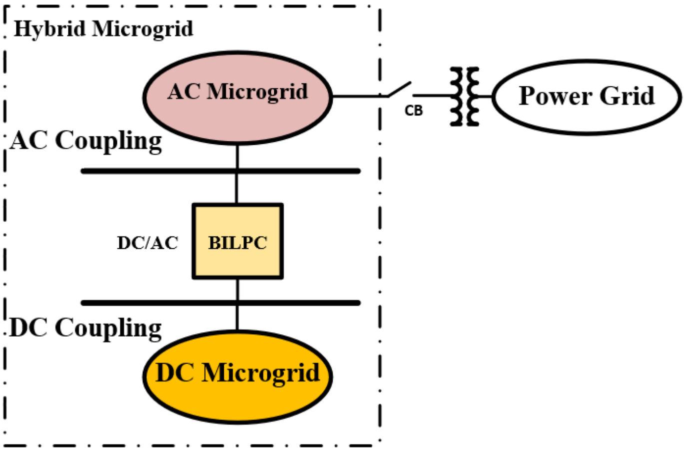


Fig. 2. Interconnection of two AC and DC microgrids using a single BILPC

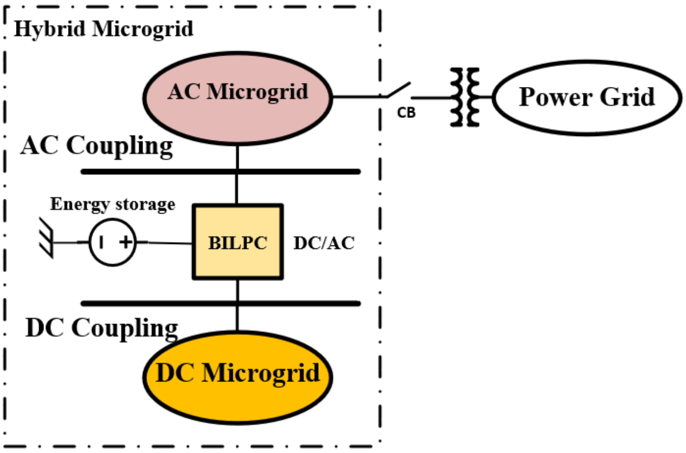


Fig. 3. A topology for BILPC connection in HMGs proposed by [40]

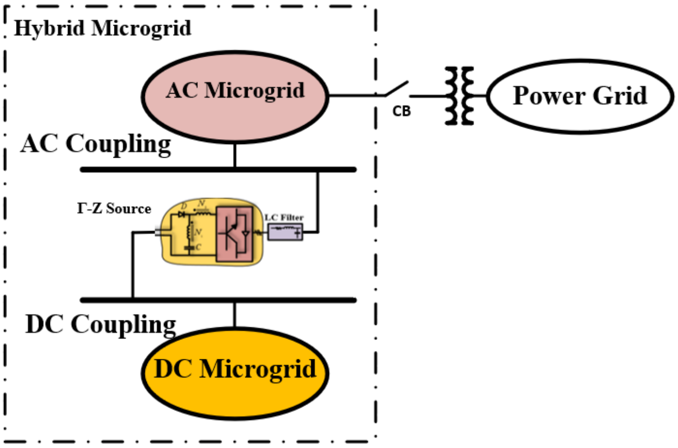


Fig. 4. Interconnection of AC and DC microgrids using a Γ-Z-Source power converter (Γ-Z-SBILPC) proposed in [41]

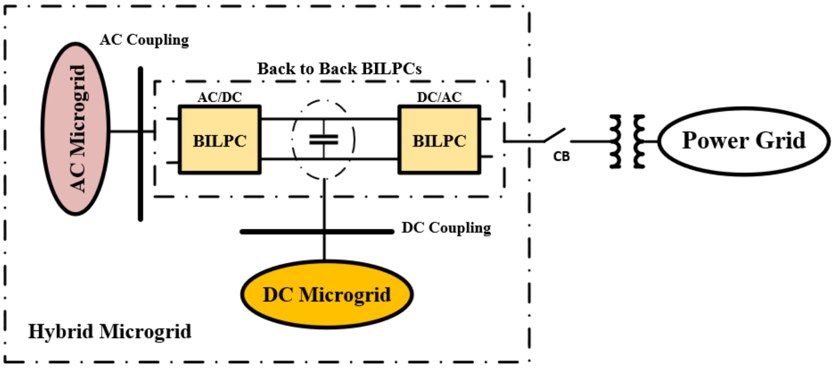


Fig. 5. Using back-to-back BILPCs to interconnect an HMG as presented in [42]

2.2.Interconnection of HMGs using parallel-connected BILPCs

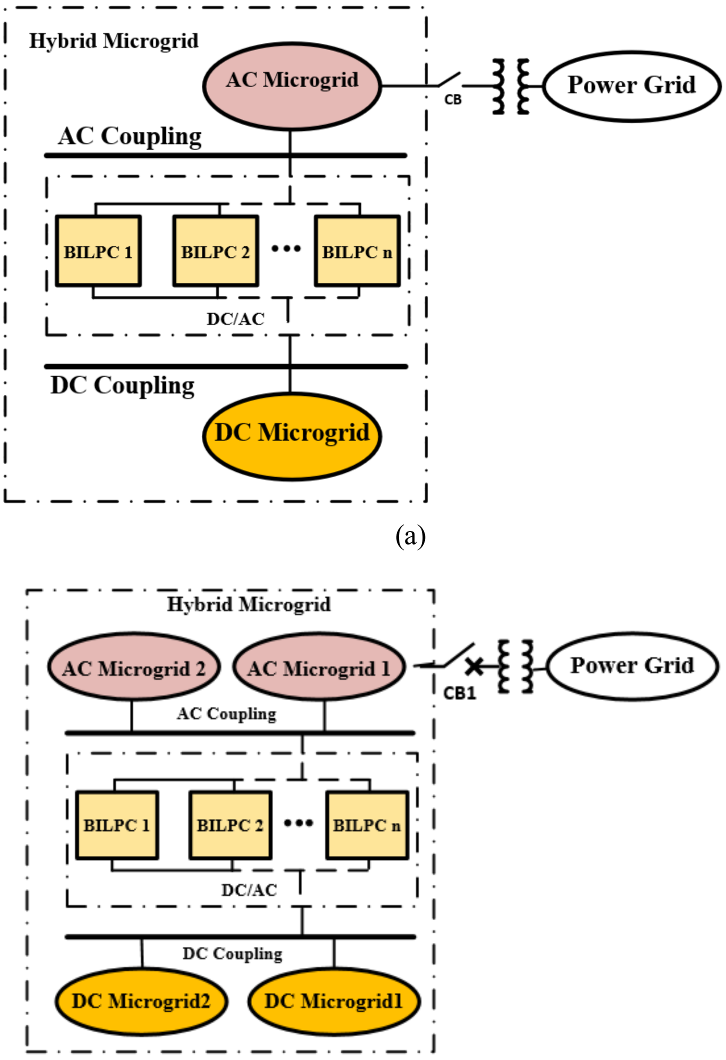
To increase exchanged power among interconnected microgrids and also the reliability, the BILPCs are usually connected in parallel. This configuration has been considered in many researches to present different control strategies, which will be discussed in the next section. Fig. 6 (a) shows the interconnection of two microgrids while Fig. 6 (b) indicates the interconnections of more microgrids using the parallel-connected BILPCs. However, when connecting in parallel, many control challenges appear in control design and operation levels. The parallel operation and control of BILPCs in an HMG is challenging task due to the following facts:

- As mentioned in the previous subsection, HMGs present a heterogeneous system. In such configuration, the control and parallel operation of BILPCs are challenging because the output voltage of each BILPC must be equal to remove circulating current, and power losses and provide a stable power exchange operation between the DC and AC sides [33, 35, 94].

- If the parallel-connected BILPCs have equal power ratings, the control system must provide equal power sharing for the BILPCs. In general, the exchanged power between DC and AC sides must be shared among the BILPCs according to the power rating of each BILPC; the higher the power rating of a BILPC, the larger the share of the exchanged power [92, 95].

- The power sharing and exchanged power between the DC and AC sides are affected by the changes in the system parameters, for instance, change in line resistance or inductance, or loads. In this condition, the power transferring through each BILPC may change and results in circulation current and power losses, or even worse, the power exchange corruption due to protection system function [2, 13, 92, 96].
- When a fault occurs in a microgrid or in AC Coupling or DC Couplings buses, for example a symmetrical/unsymmetrical short-circuit fault, the fault current inclines to unequally be divided among the BILPCs. This may result in increase in the current passing through a BILPC and finally disconnect it from the system because of fast response of protection strategies. This condition may worsen by transferring the power share of the disconnected BILPCs to other BILPCs to supply the demanded power. Thus, this may result in disconnection of other BILPCs and therefore, losing the exchanged power, the same as blackout phenomenon in conventional power systems. To handle this problem, the control system must robustly act and limit the exchanged power among the in-service BILPCs with new appropriate power sharing or a load shading strategy must be taken [43, 46, 92, 97].
- Again, due to uncertainties in system model, designing control systems considering such uncertainties is a challenging task, to provide appropriate power sharing among parallel BILPCs, which has been well-studied by many researches [33, 47, 98].
- The nonlinear phenomena, for example, the harmonics etc., cause phase deviation at output voltage of parallel-connected BILPCs. The control system is expected to handle these distortions in order to facilitate appropriate power sharing and reduce power losses and voltage drop [99-101].
- The BILPCs may operate with different power factors due to system conditions. Again, this means changes in phase and output voltages of BILPCs and must be handled by the BILPCs control system [43, 102, 103].
- Similar to the single BILPC, the parallel-connected BILPCs should be able to do different control tasks in different operation modes. However, since there are some couplings between some control parameters, for example, the DC link of all BILPCs, the control design is more complex [46, 92, 104].
- The stability of the DC and AC links again is a major concern. In fact, The DC link voltage is prone to instability for the parallel-connected BILPCs more than a single BILPC. This is due to the common coupling of DC sides of the BILPCs. Therefore, the control system of the parallel-connected BILPCs should be more elaborated to counteract this problem [45, 105, 106].

Therefore, a sophisticated control system should handle all/some of abovementioned challenges as much as possible. Many researchers have tried to overcome these challenges by presenting various control strategies for the parallel-connected BILPCs which will be reviewed in the next section.



(a)

(b)

Fig. 6. Topology of typical HMGs interconnected by parallel-connected BILPCs: (a) interconnection of two microgrids, and (b) interconnection of more microgrids

2.3.Interconnection of HMGs using SST

The conventional power transformers have widely been used to interconnect power systems with different voltage levels. For example, interconnection of medium-voltage (MV) lines with low-voltage (LV) buses. However, these voluminous power transformers present lower flexibility in future smart grids and increase the system losses by adding passive impedance into the transmission lines. The integration of DGs and ESSs in power system can be facilitated by implementation of SSTs. The main advantage of an SST is that it provides a LV DC link which makes the integration of DGs and ESSs easy. Also, the SST includes a DC/DC power converter which operates at a medium frequency which drastically reduces the size of passive elements, resulting in lower cost and loss. Furthermore, since the SST is basically a power electronics-based component, by implementation of power converters, it enjoys all flexibilities related to control of power converters for various purposes in power systems. For example, the power quality, reactive power compensation and voltage control, and active and reactive power exchange control performance can be provided by the SST.

Different topologies for SSTs and their applications in smart grids have been reviewed in [107] and [108]. The SST has been used as an alternative for BILPCs to interconnect HMGs. For example, in [76], an HMG has been interconnected by an SST, where one AC microgrid, one DC microgrid, and AC power system have been tied through AC and DC links of the SST. This topology is illustrated in Fig. 7. The authors have proposed a distributed power management strategy focused on the DC side. The droop-based control scheme has been proposed by concentrating on the batteries as effective tools for regulating the DC side power and voltage. The SST has enabled the proposed structure with bidirectional power flow. Also, active charging/discharging control of the battery package has been provided by the proposed power management strategy.

As another example, in [77], an HMG with different voltage levels, includes MV- and LV-AC buss, a MV-DC microgrid, and a LV-DC microgrid. This structure is illustrated in Fig. 8. As shown, the SST is located between two AC buses and also interconnects the DC microgrids. The main objective was to show the effectiveness of the SST in supplying loads during a fault in comparison to the conventional power transformers. The simulation results have indicated that when one phase is corrupted in the conventional power transformer-based connections, the transformer is overloaded, resulting in more unsupplied loads. However, the SST has removed this problem by suitable power exchange control among the microgrids and the AC buses.

The authors in [78] has used an SST to interconnect a DC microgrid with AC loads and power system. The DC microgrid consists of a PV system and a battery as ESS. The SST has a modular three-layer topology which can integrate a LV-DC microgrid with the power system. The behavior of the SST during faults has been investigated. Also, it has been indicated that the SST is an effective tool to reduce power quality problems, for example, voltage sages etc. In [79], the SST has been implemented to interconnect DC microgrids, AC loads and power system. The DGs have operated in maximum power point tracking (MPPT) mode and a new power management strategy has been proposed for the whole system. By following this approach, a uniform and integrated power management for the AC and DC sides have been attained. Also, the power factor correction feature has been obtained and the system reliability has noticeably been enhanced.

In comparison to the BILPC-based interconnections, the SST-based interconnection of HMGs can be characterized as follows:

- The parallel-connected BILPCs bring many technical issues as described in the previous subsection. For example, power sharing, synchronization of output voltages of BILPCs etc.
- The SST provides bidirectional power exchange control among subsystems and the BILPCs, as well.
- The SST presents more features and flexibility for the distribution system. For example, the power factor correction, reactive power compensation and voltage control, disturbance separation, active filtering of harmonics, fast and intelligent protection capability, etc.
- A DC/DC power converter with medium frequency is needed for the SST. This power converter provides galvanic isolation for the system.
- A coordinated control system should be provided for the AC/DC, DC/DC, and DC/AC power converters of an SST unit.
- The DC link oscillations control of an SST is a challenge yet.

- When connecting to an upstream grid through BILPCs, the performance of these power converters is highly affected by the grid impedance characteristics. Actually, the stability of the grid-connected BILPCs is affected by X/R ratio of the grid and should be considered in the controller design. It is shown that the SST can reduce these side-effects by shaping the grid impedance and improve the stability of local controllers and grid.

Therefore, interconnection of HMGs using the SST is less challenging in comparison to the parallel-connected BILPCs.

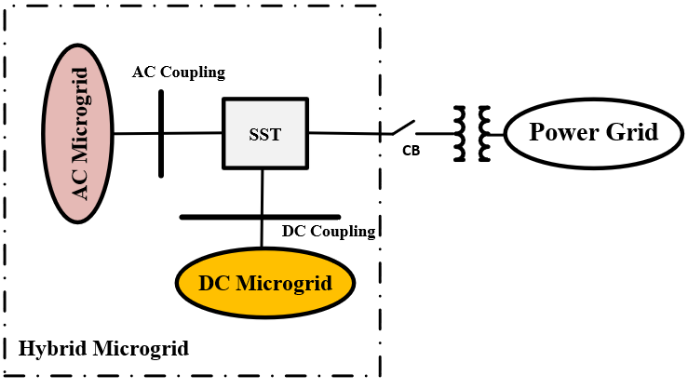


Fig. 7. AC and DC microgrids interconnected by SST, as proposed by [76]

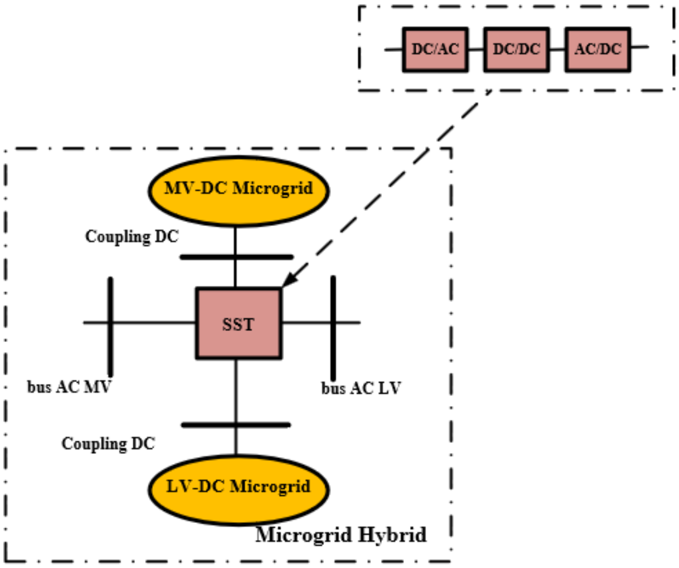


Fig. 8. Interconnection of an HMG with different voltage levels using SST, as presented in [77]

2.4. Energy Router-based HMGs

The concept of ER to interconnect an HMG has been discussed in [80]. As indicated in Fig. 9, an ER consists of several DC/AC and DC/DC conversions to interconnect several microgrids with different characteristics. The DC/AC conversion units facilitate the connection of AC microgrids with different frequencies. On the other hand, the DC/DC units are implemented to adopt the DC outputs of DC microgrids, which may have different output voltage levels, with the DC coupling voltage of the common DC bus of ER.

Then, the rectified voltage is converted to AC using a DC/AC unit, called the main power converter. This power converter is actually a BILPC which enables bidirectional power exchange between the AC power system and the HMG. A power management strategy, based on dual-loop feedback control, has also been presented in [80] which avoids using ESSs, resulting in lower cost. The multi-port ER has been used to interconnect microgrids with different consumption/generation pattern. Specifically, the residential and commercial loads have been included in different microgrids. The ER has been able to compensate the power shortage in each microgrid when necessary.

For the ERs, the most important challenges are as follows:

- The ERs must carry relatively high output currents and high input voltages. Therefore, from the design perspective, these devices are more complex than BILPCs.
- The ERs' efficiency, cost, and reliability problems increase because of using several power conversion units.
- The grid-side DC/AC power converter is usually designed with redundancy which increases the cost. The reliability of the ER is highly affected by this power converter; if this unit fails, the HMG is disconnected from the main grid, which in turn may results in instability if there is not any preassigned control measure.
- The DC link voltage stability is a problem. A stiff control strategy should support this link due to several connections of power conversion units.
- The ERs are economic for HMGs with more DC sources than AC ones.

If addressed suitably, these problems would be reduced by the control systems and therefore, the ER could be used as an effective tool to interconnect HMGs.

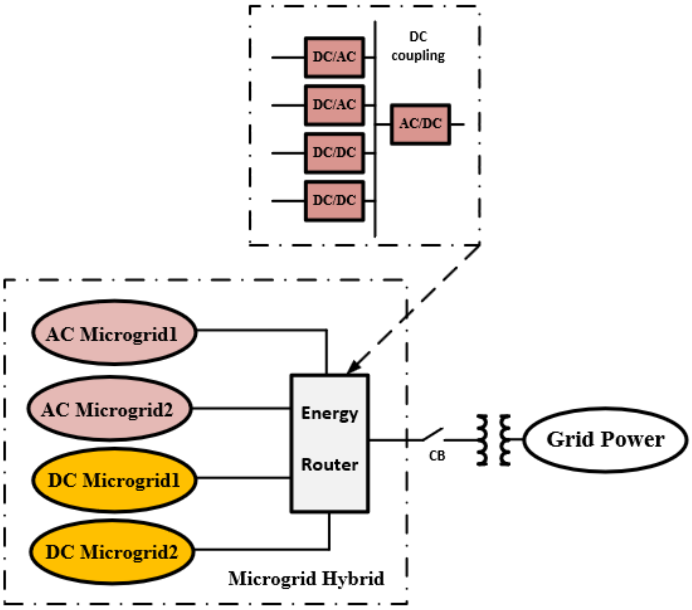


Fig. 9. The ER concept to interconnect HMGs, as proposed in [80], and [81]

2.5.Small-Scaled FACTS for Interconnection of HMGs

The FACTS devices have already been used in large-scale power systems to control power flow [109], reactive power compensation [110], and enhancing power system stability [111-113]. In recent years, some researchers have tried to use these devices in microgrids applications.

These efforts have been based on some modifications in the model or control systems of these small-scaled FACTS to make them compatible with microgrids dynamic characteristics. The UPFC, UPQC and UIPC are FACTS devices which have been adopted well with HMGs.

2.5.1. Interconnection of HMGs using UPFC

In [82], the authors have proposed an HMG topology based on UPFC. This structure is shown in Fig. 10. The UPFC has a series and a parallel power converter with a common DC link. Here, the DC link is supported by a DC/DC power converter to accommodate the DGs and loads and provide DC link voltage regulation and power decoupling feature. The series power converter is then connected to the power grid using an isolation transformer in the conventional UPFC structure, however, the proposed model in [82] has removed these costly transformers; both at DC and AC sides. The DC link here is fed by the DGs, however, a DC microgrid would be a good choice to supply it, since the DC microgrid can accommodate more DGs and loads with a regulated output. The electrical circuit of the proposed structure has been detailed in [82] and the functionalities of the model have been identified. The authors have also presented a modular structure which enables the HMGs to integrate more DGs and local microgrids. The control systems for each power converter have been developed in αβ frame and the frequency response of the controllers and closed-loop systems have been analyzed to ensure the stability during connections of variable DGs.

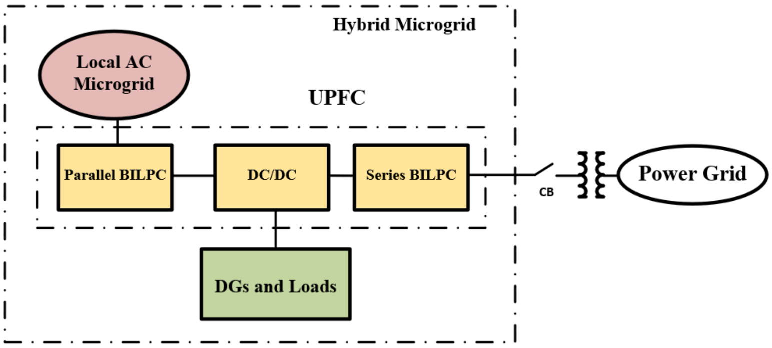


Fig. 10. An HMG interconnected by UPFC, as proposed in [82]

2.5.2. Interconnection of HMGs using UPQC

The UPQC is one of Custom Power devices (CUPs) which has been used as a generalized device to improve power quality issues in power systems. The CUP operation in distribution systems is almost similar to the operation of FACTS devices in transmission lines. Several power quality issues can be addressed by the UPQC. For example, harmonic reduction, reactive power compensation and voltage control, and in general, reduction of effects of disturbances on the power supply. The UPQC has a DC link which is common between its series and parallel power converters. This DC link can be connected to DC sources or a DC microgrid [83]. In this condition, the UPQC enables the distribution system with active power flow control capability. Therefore, this feature makes the UPQC an effective tool for both power quality improvement and power flow control purposes. Such scheme has been followed in [84], where the authors have used a UPQC for interconnection of an HMG. The UPQC model has been reformed and named as UPQC-DC. The topology of the HMG is illustrated in Fig. 11.

As shown, two BILPCs have been used to form a back-to-back topology. These power converters along with a series power transformer shape the UPQC-DC with a common DC bus which has been connected to a DC microgrid. This structure provides power flow capability, reactive power injection/consumption, voltage control, power fluctuation reduction and power quality improvement. The BILPC have been supported by a control scheme developed in *dq* reference frame based on instantaneous values of the system measurements. The proposed control has been able to counteract power quality problems, for instance, voltage sag and swell and voltage unbalance.

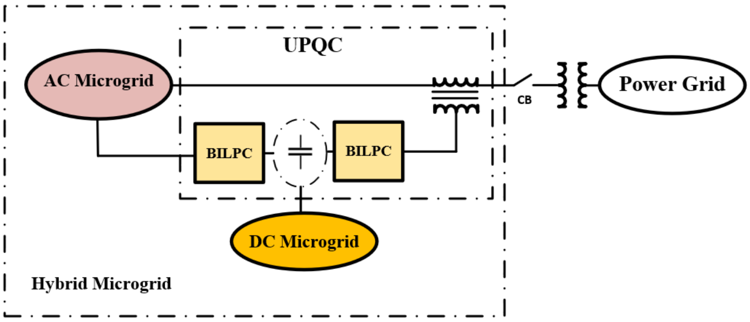


Fig. 11. An HMG interconnected by UPQC presented in [84]

2.5.3. Interconnection of HMGs using UIPC

The conventional interphase power controller (IPC), which is one of FACTS devices, has been suggested in transmission lines of large-scale power systems. This device has been connected in series with transmission line and injects series voltage into lines through phase shifting transformers. The injected voltage changes the amplitudes and phase of the line current which results in power flow control between two AC buses in the power system. In [114], however, the conventional structure of the IPC has been revised by replacement of phase shifting transformers with voltage source converters. This resulted in more degrees of freedom for power control, lower loss, and inherent fault protected feature. The topology has been named as UIPC which has been used for power flow control and voltage regulation between two AC buses in bulk power systems. Of late, a modified UIPC has been reported in [92] which is useful for interconnection of HMGs.

In the modified version of the UIPC, in comparison to its conventional model in [114], the number of power converters and series power transformers has been reduced. Also, the DC link of the UIPC has been connected to a DC microgrid. Because the output voltage and power of the DC microgrid is fluctuating, a stiff observer-based sliding mode control strategy has been used for the power converter of the DC link, named as bus power converter (BPC). The structure of an HMG interconnected by the UIPC is illustrated in Fig. 12.

In this topology, the BPC is responsible for DC voltage stabilization and power exchange control between the AC side and the DC side. There is also another power converter which has been connected in series with the transmission line, named as line power converter (LPC). The LPC is responsible to inject a controllable series voltage into the transmission line. In this way, the power flow between two AC buses can flexibly be provided. Therefore, The UIPC has been able to provide bidirectional power flow among AC and DC systems with voltage regulation capability.

The same authors have also developed this structure in [33] to accommodate a greater number of microgrids. This topology is indicated in Fig. 13, where groups of AC and DC microgrids can be interconnected by the UIPC. Such a topology has provided flexible power flow between the main power system and the AC and DC microgrids.

The main advantages and disadvantages/challenges of the abovementioned interconnection methods of AC and DC microgrids in HMGs are summarized in Table 2.

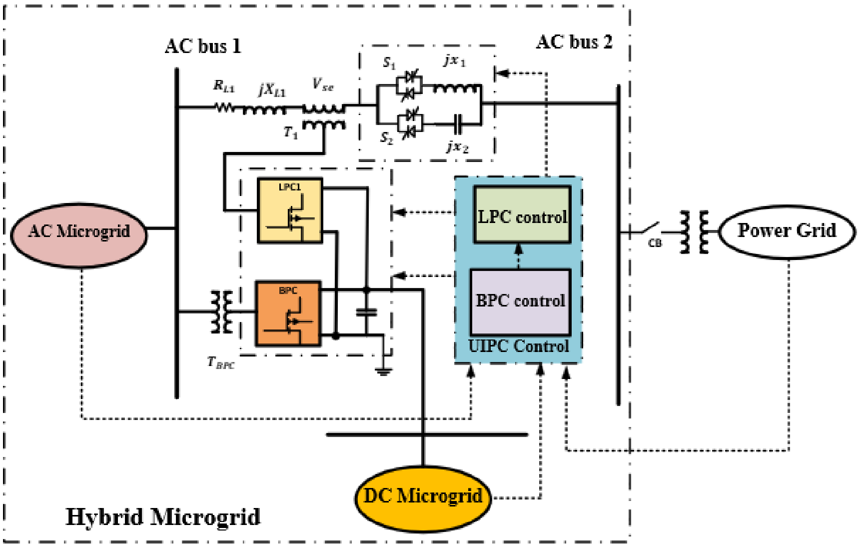


Fig. 12. Per-phase model of UIPC forming an HMG [92]

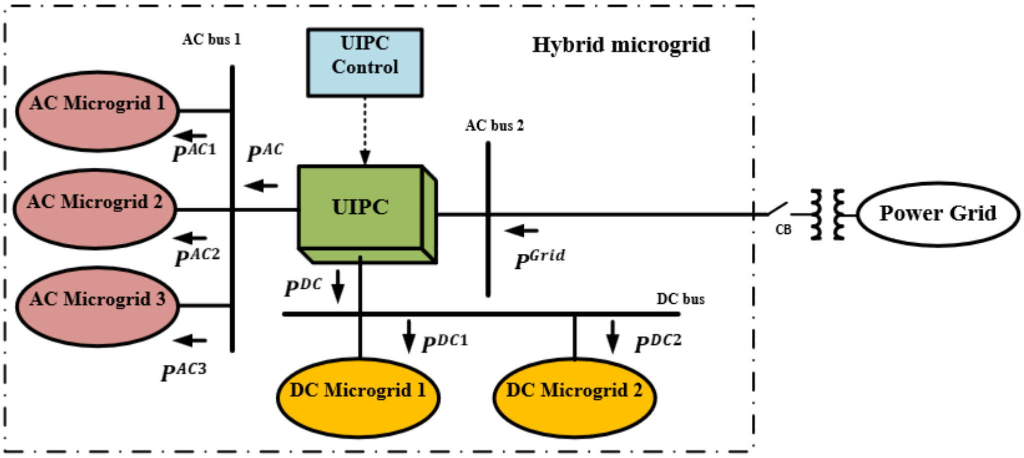


Fig. 13. Multiple AC and DC microgrids interconnected by UIPC [33]

Table 2. Main advantages and disadvantages/challenges of interconnection methods of AC and DC microgrids in HMs

Single BILPC	-Lower cost and simple control. -A Single UIPC can be equipped with an ESS to make the DC side more reliable and fault-tolerant. -Some structure for BILPC, for example, Γ-Z-SBILPC higher efficiency and reliability in comparison to the conventional BILPCs.	-The amount of transferred power is limited -Lower reliability. -Closed-loop system stability and output response, is crucial for a single BILPC to have a stable operation and present flexible power exchange capability -The stability of the DC link is an important issue which should be addressed.
Parallel BILPCs	- Higher reliability. -Larger amount of power can be transferred between the AC and DC sides. -Modular base structure.	- Higher cost and complex control. -Circulation current and power losses problem. -Setting equal power sharing according to power ratings of BILPCs is challenging. -Keeping the voltage stability is a challenge.
SST	-The SST provides bidirectional power exchanges between subsystems without problems related to parallel-connected BILPCs. -The SST presents more features and flexibility for the distribution system. For example, the power factor correction, reactive power compensation and voltage control, disturbance separation, active filtering of harmonics, fast and intelligent protection capability. -Galvanic isolation feature.	-A complex control (for coordination of the AC/DC, DC/DC, and DC/AC power converters). -The DC link oscillations control challenges. -The stability of the grid-connected BILPCs is affected by X/R ratio of the grid which is a challenge in the controller design.

Table 2. Continued

ER	-The ERs are economic for HMGs with more DC sources than AC ones. -A multi-port power converter can be used in ER structure which its control is simpler and its cost is lower in some cases (for example, in comparison with parallel-connected BILPCs).	-The ERs must carry relatively high output currents and high input voltages. Therefore, from the design perspective, these devices are more complex than BILPCs. -Efficiency, cost, and reliability problems. -The reliability of the ER is highly affected by its redundant power converter. -The DC link voltage stability is a problem.
Small-scale FACTS	- Higher reliability. -Larger amount of power can be transferred between the AC and DC sides. - Swift and robust bidirectional active and reactive power flow between AC and DC microgrids. -Providing DC link voltage regulation. -The DC microgrid can accommodate more DGs and loads with a regulated output. -The power quality problem can be resolved by these devices while the bidirectional power flow feature is also provided.	-Costly transformers in some cases (for example, when using the conventional structures of UPFC or UIPC). -Control of series and parallel power converters of UPQC is challenging when connecting the DC side to a DC microgrid.

3. Overview and Classification of BILPCs Control Strategies

Until now, the interconnection methods of HMGs have been classified and reviewed. As mentioned before, many researchers have concentrated on interconnecting HMGs using single and parallel-connected BILPCs, and therefore, various control strategies have been proposed for them. In this part of study, the control strategies for the BILPCs described in literature are classified and reviewed, first based on architecture and then based on control method.

3.1.General Classification and Specifications

By investigating the literature, the control architectures can be classified into centralized and non-centralized, as demonstrated in Fig. 14. This classification refers to the basic structure of the control strategy which presents different characteristics. Table 3 presents general specifications of each structure. The centralized configurations mainly require communication links among the BILPCs controllers. Moreover, more measurements are required. On the other hand, non-centralized configurations need no communications links. Accordingly, the reliability of the centralized configurations is lower than the other ones, as indicated in Table 3. It should be mentioned that the non-centralized configurations have been classified here to decentralized, distributed, and hierarchical control architectures. Fig. 15 shows the conceptual scheme of all the configurations. Table 3 represents other specifications of the architectures in brief. To be more specific, the specifications of each architecture are distinguished, as follows:

1) The main features of the centralized control architectures are:

- The BILPCs are independent.
- There is one controller for all the BILPCs, commonly named as "central controller", as illustrated in Fig. 15 (a).
- A unique control signal is sent to each BILPC by the central controller.
- All of the computations are done in the central controller and then, the command signals are sent to the pulse width modulation (PWM) units of BILPCs.
- The reliability of the centralized architectures is a concern because of loss of a communication link or failure in the central controller.
- The optimality of the control strategies based on this architecture is possible and the control and operational objectives can be satisfied.
- The system dimension is large. This results in high costs and also slow dynamic response because of time constants in command signals etc.
- The computational burden of the centralized controller is high. This is a concern for online and real time applications.

2) For the non-centralized architectures, the following specifications can be expressed:

➢ Decentralized control architecture:

- According to Fig. 15 (b), each subsystem, i.e., BILPC, has its own controller.
- The subsystems have interactions and share some information.
- There are feedback signals directly from the output to the controllers.
- Higher reliability in comparison to the centralized architecture due to loss of communication links and lack of a central controller.
- The optimality for each BILPC is provided, but the whole system may work in sub-optimal conditions.

- ➢ Distributed control architecture: Besides the main specifications of the decentralized architecture, this architecture has the following features:
- The information sharing among the controllers is provided, as shown in Fig. 15 (c).
- Higher reliability in comparison to the centralized architecture.
- From the BILPCs point of view, the distributed architecture-based control algorithms can be classified as: a) completely interconnected algorithms, and b) partially interconnected algorithms. Each of these algorithms has its own property; based on control objective, cost, reliability and so forth.
- From the controllers' point of view, the distributed architecture-based control algorithms can be classified as: a) non-repetitive algorithms, where the data is exchanged among the local controllers only once during a time interval, and b) repetitive algorithms, where the data is exchanged among the local controllers several times during a time interval.
- Based on the performance index, the distributed architecture-based control algorithms are categorized as follows: a) independent algorithms, where each local controller optimizes its local performance index, and b) cooperative algorithms, where each local controller participates in optimization of a global performance index.
- ➢ Hierarchical control structure:
- As demonstrated in Fig. 15 (d), the hierarchical architecture is a combination of decentralized and distributed architectures. There is an upstream control level which commands the lower control levels.
- It includes three control levels: a) primary level, which is responsible for voltage regulation or reference current/power tracking, voltage stability, appropriate power sharing, and reducing/removing circulating current, b) secondary level, which its main purpose is to provide set-points for the primary level and is responsible for preventing of voltage and frequency steady state deviations, improving power quality, and removing the errors raised by the action of the primary control level, and c) tertiary level, which is used for defining steady stated set-points, power market requirements, and optimal power flow.
- The primary level is the fastest control layer in a hierarchical architecture.
- The hierarchical architecture-based control strategies described in literature are mainly based on droop control.

Table 4 presents some references according to abovementioned categorization of BILPCs control architectures.

According to HMG operation mode, the control strategies may accomplish different tasks. An HMG may be connected to an upstream grid, i.e., grid-connected mode, or it can be isolated from the power grid, i.e., islanded mode, as shown in Fig. 14. In fact, an HMG may switch to islanded mode due to planned operational purposes or due to fault in upstream grid. Thus, from this point of view, the islanding by itself can be classified as intentional or non-intentional. Anyway, the operation mode of the HMG results in change BILPCs control strategy. Mainly, in the grid-connected mode, the BILPCs should operate in power control mode. The HMG exchanges power with the upstream power grid and the BILPCs are forced to exchange power between the sub-systems, i.e., the interconnected AC and DC microgrids. The voltage and frequency of the HMG are controlled by the upstream grid.

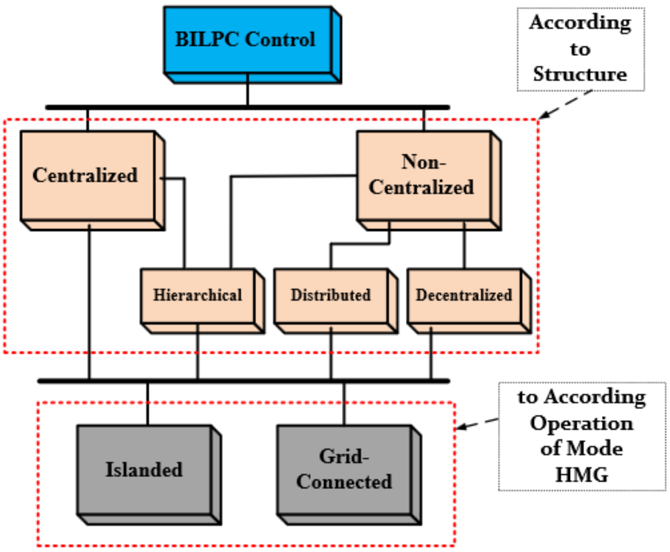


Fig. 14. General classification of BILPCs control strategies based on structure of control and operation modes of HMG

Table 3. General specifications of centralized and non-centralized control of BILPCs in HMG

Communication-based	Mainly dependent	Partially/not dependent
Reliability	Low	High
Power sharing among BILPCs	Higher	Lower
Information sharing among BILPCs controllers	High	Low
Adding-up new BILPC	Needs changes in the configuration	Plug-and-play
Computation cost of the BILPCs controller	High	Low
Optimality of control objectives	Optimal	Sub-optimal
Response speed	Low	High
System dimension	Large	Small

Table 4. Some references according to control architecture categorization

Centralized	[48], [49]
Decentralized	[50], [51], [115], [43], [46], [45], [44]
Distributed	[52], [53], [54], [55], [56]
Hierarchical	[82], [57], [58]

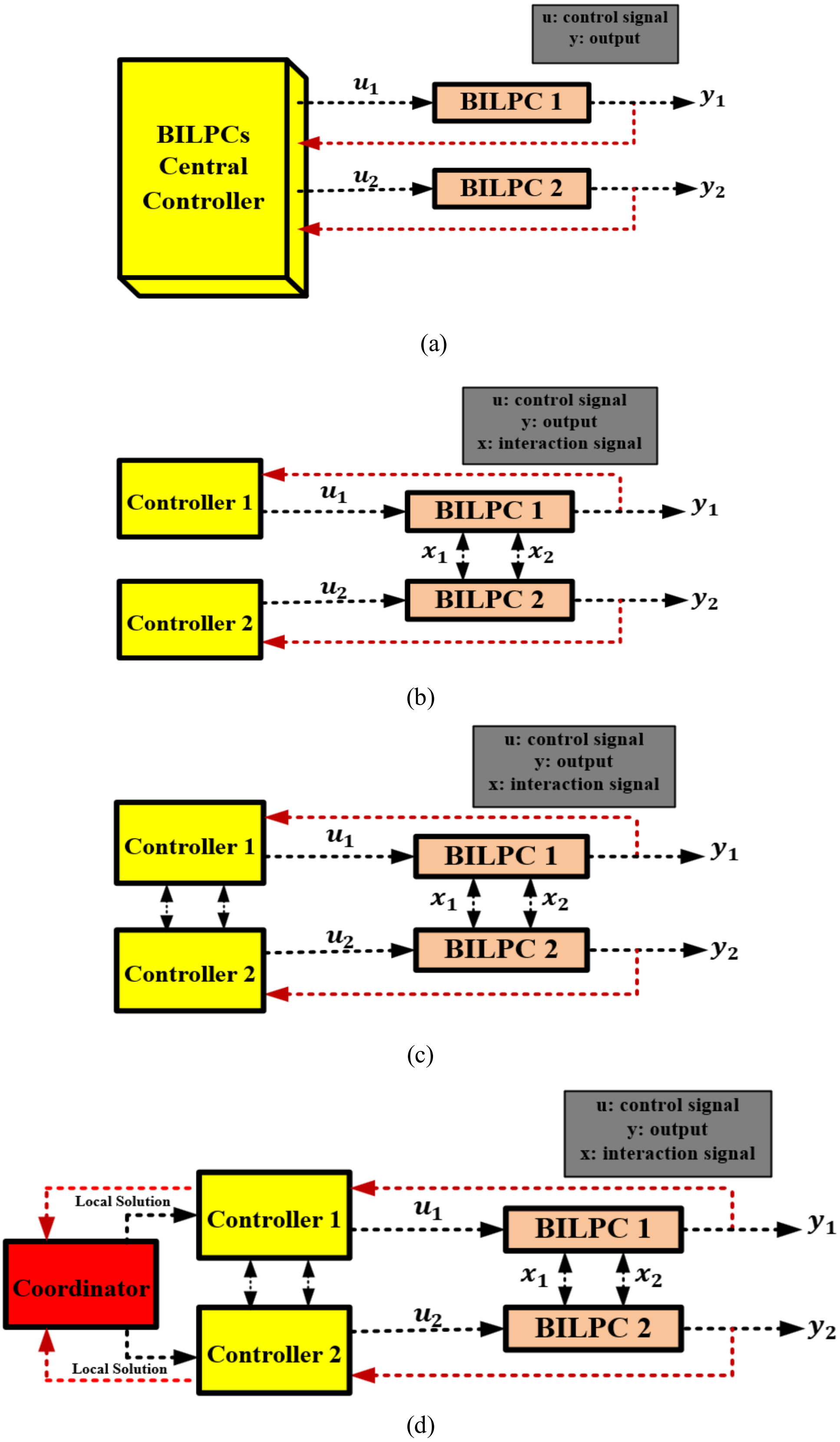


Fig. 15. Different control architectures for BILPCs: (a) centralized, (b) decentralized, (c) distributed, and (d) hierarchical

3.2.Overview of Control Methods

Fig. 16 demonstrates the categorization of various control methods of the BILPCs, by investigating the literature. As shown, the control methods have been divided into five major groups: 1) droop-based methods, which includes conventional droop, virtual impedance, and adaptive or improved robust droop methods, which encompasses linear matrix inequality (LMI)-based, linear quadratic regulating-based, and data-driven droop control methods, 2) intelligent control, which is related to fuzzy logic and artificial neural network-based control methods used for BILPCs, 3) robust, observer-based, and optimal control methods, which consists of LMI-based and sliding mode control (SMC) methods, 4) active power sharing methods, which includes instantaneous active current sharing (IACS), master-slave, and circular chain methods, and 5) instantaneous power theory-based methods. Table 5 presents some research works according to this classification.

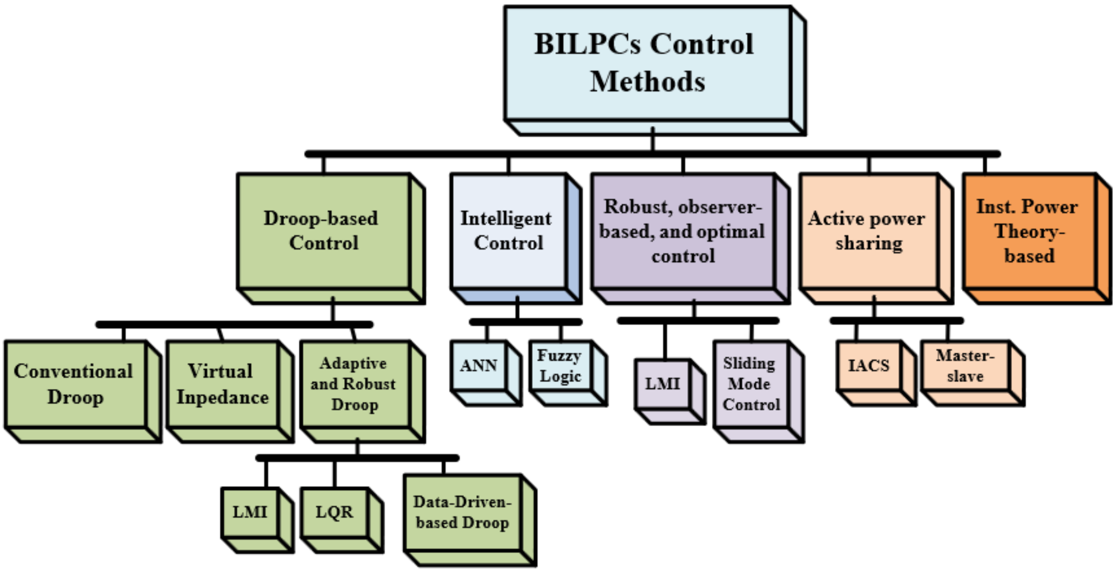


Fig. 16. Classification of various control methods of BILPCs

Table 5. Some research works according to classification of Fig. 16

Droop-based	Conventional	[59], [60], [48], [61], [62], [58], [63]
	Virtual Impedance	[64]
	Adaptive, Improved and Robust	[50], [53], [51], [52], [39], [49], [54], [65], [56], [66]
Intelligent Control	Fuzzy Logic	[67]
	ANN	[68], [69]
Robust, Observer-based and Optimal Control	LMI	[116]
	Robust, Observer and SMC-based	[47], [55], [70], [45], [44]
Active Power Sharing	Master-Slave	[71], [72], [73]
	IACS	[74]
Instantaneous Power Theory-based		[46], [43]

3.2.1. Droop-based Control Methods

Generally, the conventional droop control method is based on two main droop characteristics; $P-\omega$ and $Q-V$, as follows:

$$\omega_n = \omega_{rated} - \alpha_n P_n \tag{1}$$

$$V_n = V_{rated} - \beta_n Q_n \tag{2}$$

where, n is the number of the BILPC, ω is frequency in rad/s and ω_{rated} is its rated value, V is the output voltage of each BILPC and V_{rated} is its rated value, P_n and Q_n are, respectively, the active and reactive power of BILPC, α_n and β_n are the droop coefficients. The droop equations design may vary when studying HMGs operation modes. More details can be found in the references identified in Table 5. Further, the main feature of virtual impedance-based droop is according to adding a mainly inductive impedance to the equation of reference output as follows:

$$V_{ref} = V_{out} - Z_{virtual} I_{out} \tag{3}$$

where V_{out} and I_{out}, respectively, are the output voltage and output current of BILPC, and $Z_{virtual}$ is the designed virtual impedance which is resulted from the control loop system fast dynamic behavior and mimics the line impedance. In the adaptive droop schemes, the droop characteristics adopts variable droops based on some conditions. For example, for the active power we can have such relationship:

$$V_n = V_{rated} - \beta_n Q_n - \beta_{n,add}(Q_{max} - Q_{ref}) \tag{4}$$

In this scheme, the maximum reactive power Q_{max}, which can be drawn from each BILPC is registered and compared to a reference value Q_{ref}. If $Q_{max} < Q_{ref}$, then the conventional droop scheme is followed; else, $\beta_{n,add}(Q_{max} - Q_{ref})$ is subtracted from the voltage droop characteristic, resulting in a variation in slope of the characteristic line.

In the robust droop control schemes, a commonly used relationship for the droop characteristics is as follows:

$$E_n = K_e\left(E_{n,rated} - V_{out}\right) - \delta_n P_n \tag{5}$$

$$\omega_n = \omega_{rated} - \gamma_n Q_n \tag{6}$$

where E_n is the output voltage (internal) of BILPC before filter series drop, K_e is a constant, and δ_n and γ_n are the so-called robust droop coefficients which should be determined appropriately.

For the most part, the literature is enriched with the droop-based control methods of the BILPCs. For example, considering the same structure of Fig. 2, the authors in [61] have presented a coordinated control scheme for a BILPC in a typical HMG. The studied system has been simplified in which the DC microgrid contains a PV and a battery storage system, and the AC microgrid includes a wind turbine. The proposed coordinated control algorithm has successfully been able to provide an appropriate cooperation between the boost converter of DC system and BILPC; operating in both grid-connected and islanded modes.

A droop control scheme for a BILPC has also been presented in [65]. The BILPC control has been coordinated with an ESS. Besides, the control of the DC link has been accomplished to reflects the effects of the DC link capacitor. An improved droop control has been described in [60], where an HMG including an AC microgrid and a DC microgrid have been tied using a BILPC. The control method is capable of controlling the power transfer between the microgrids in both grid-connected and islanded modes. In the grid-connected mode, the control system tries to sustain the DC link voltage stable while keeping the most efficiency of the DC resources in the DC microgrid. In the islanded mode, the dynamic performance of the whole HMG is improved by appropriate power distribution between the two microgrids. Considering a droop control concept, a hierarchical control strategy has been described for BILPCs in [62]. The DC voltage control and power management have been provided and the system has been augmented against unsmooth switching transitions. The control strategy is multi-functional and has been able to simultaneously provide voltage support and power management.

In [48], a multi-objective control algorithm has been described for BILPCs. The studied system includes several AC and DC microgrids with various loads and sources. These microgrids have been connected to a common AC bus. Thus, the whole system is an HMG with different subsystems. Each BILPC has been equipped with a local controller which uses droop-based regulation and can communicate with a central controller. Therefore, the whole control system is a streamlined centralized strategy. The authors in [59] have studied the output voltage synchronization of a BILPC and power exchange control between AC and DC microgrids in an HMG. A droop control method has been proposed to control the BILPC such that the magnitude and phase of the output voltage of the BILPC are the same as those of the AC link of the AC microgrid. Considering the islanded mode of operation, a coordinated droop-based control method for the BILPC has been presented in [117]. The main purpose of this method has been set to provide proper power sharing among the interconnected microgrids and also improve the operational reliability. In [58], a dual-loop droop-based control strategy has been described for parallel-connected BILPCs. The general structure has used a hierarchy concept which has been implemented in *dq*-reference frame and the main purpose of the control design was removing zero-sequence circulating current among BILPCs. Furthermore, a recovery control block has been used to improve the power quality and reliability of the HMG. Considering an HMG system including several AC and DC microgrids, a dual-loop droop control-based method has been proposed in [115]. The studied AC and DC microgrids had different voltages and frequencies and all storage systems have been considered as a lumped unit to simplify the control design and power transferring performance.

In [57], a hierarchical control method has been proposed to control a system of parallel BILPCs. Again, the droop concept has been the basic of the control design, and appropriate load sharing and the DC link voltage have been attained by the proposed method. The authors in [63] have studied the instability phenomenon in HMG due to limit cycle occurrence in droop controlled BILPCs. Considering the virtual impedance concept, in [64] an improved droop control method has been proposed for multiple parallel-connected BILPCs. This method first has detected the power and current differences deviations and then tried to reduce these differences. The authors in [50] have proposed a modified droop control method which has been able to counteract the interaction between the frequency of AC side and DC voltage.

The authors in [53] have studied two independent AC and DC microgrids intertied by BILPCs. The BILPC has used a droop control and mainly aimed on transferring reactive power among the microgrids. In [51], based on an LMI approach, a droop control scheme has been presented. The exponential weightings have been set for current regulation in BILPC control loops. A distributed droop control has also been described in [52], where again the *f-P* and *V-Q* characteristics have been adopted and regulated. Moreover, a droop control-based scheme has been discussed in [39], where the voltage stability has been considered. The proposed scheme has been able to control the HMG both in grid-connected and islanded modes.

Considering a centralized droop-based control strategy for a grid-connected HMG and interlinking power converter, the power dispatching and management has been studied in HMG. In [54], a distributed control-based algorithm has been proposed where the DC microgrid contains PV, diesel generator, ESS, and resistive loads and the AC microgrid consists of microturbine, wind turbine, motor drive, and domestic loads. These two microgrids have been interconnected using the three-phase BILPC and the whole system acts in islanded mode. The graph theory has been adopted to model the HMG and design the control system. The BLPC has used an inner and an outer control loop. Each DG has been equipped with a distributed controller in the second control level and cooperates with the outer control loop of the BILPC which has adapted a droop-based control scheme.

Moreover, a data-driven improved droop control has been devised in [56] for the interlinking power converters. The dual-droop control has been used with model free control to provide an adaptive droop structure. An improved droop control method for the BILPCs in HMGs has been presented in [66], where the power consumption of each microgrid has been measured first. Then, the direction of the transferred power is measured. Two droop control units have been used to control the DC link voltage and the frequency of the AC side.

3.2.2. Intelligent Control Methods

Intelligent control methods here refer to implementation of intelligent control-based algorithms, namely, fuzzy logic, artificial neural networks (ANNs) etc., in control of BILPCs in HMGs. For instance, in [67] a supervisory control scheme has been presented for power management in an HMG. The studied HMG contained two AC and DC microgrids which have been tied through a BILPC.

The supervisory control has been structured based on fuzzy logic and has been able to manage the transferred power between the two microgrids and moreover, has been capable of harnessing the maximum utilization of the renewable resources and optimal SOC in the batteries in the AC and DC microgrids. A fuzzy control-based approach generally follows a rule-based scheme where the operation modes of BILPC is configured according to the operation of AC and DC microgrids. For example, the DC side current I_{DC} can be considered as a parameter which affects the switching patterns of BILPC. For example, we may have such rules in the fuzzy inference system:

$$\begin{cases} if\ \Delta P_{DC}\ is\ PB\ and\ \Delta SoC\ is\ NB, then\ I_{DC}\ is\ PB \\ if\ \Delta P_{DC}\ is\ PB\ and\ \Delta SoC\ is\ NS, then\ I_{DC}\ is\ PB \\ if\ \Delta P_{DC}\ is\ PB\ and\ \Delta SoC\ is\ ZO, then\ I_{DC}\ is\ ZO \end{cases} \tag{7}$$

where ΔP_{DC} is changes in DC microgrid active power, ΔSoC is changes in the state-of-charge of a battery connected to the DC link of BILPC, and PB, NB, NS, and ZO, respectively stand for Positive Big, Negative Big, Negative Small, and Zero, which are the membership functions defined for the operand parameters in the fuzzified logical statements.

The authors in [68] have implemented an ANN-based controller for optimal power management and control of BILPCs in HMGs. The main purpose of this study was improving power quality, maximum utilization of energy resources, reducing fuel cost, and optimal pulse width modulation signal generation for BILPCs. In [69], an adaptive ANN-based control scheme combined with a fuzzy logic-based power management has been proposed for control and management of BILPCs and various energy resources, including fuel cell, PVs, and wind turbine, in an HMG. The proposed scheme has minimized the energy cost and MPPT for the renewable resources.

3.2.3. Robust, Observer-based and Optimal Control Methods

In [116], a robust suboptimal control scheme has been proposed for the BILPC using linear matrix inequality (LMI) approach. The demand-generation imbalance has been considered and effects of change in parameters of output filter of the BILPC on the power exchange have been verified. In [47], a robust backstepping control strategy has been rendered for a BILPC. The Lyapunov theorem has been adapted to validate stability of closed-loop system. A predictive robust control method for BILPCs has been presented in [55]. This method has addressed the power quality problems of both AC and DC microgrids in an HMG while simultaneously a stable power transfer between these microgrids has been established. In such predictive pattern, the reference voltage may be obtained according to the following equation:

$$v_{ref}(t+1) = v_{out}(t) + L_1\left(\frac{i_{L1,ref}(t+1)-i_{L1}(t)}{T_s}\right) \tag{8}$$

where L_1 is the output inductance (coupling transformer, filter…), T_s is sampling time.

Moreover, the DC link voltage stabilization property has been provided through this control method. More recently, the authors in [44] have developed a robust sliding mode control strategy for BILPCs based on observer-based control concept. The authors have indicated that the BILPC nonlinear dynamic model can be presented as two decoupled linearized subsystems which can easily be controlled using robust state feedback controllers. The model has been linearized using Lie's Derivative theorem and the Akerman Pole Placement Method. The optimal control signal in this scheme is obtained as follows:

$$u(t) = -\Gamma^{-1}(x)\begin{bmatrix} -\frac{1}{\bar{C}_f\bar{L}_f}x_3 \\ -\frac{1}{\bar{C}_f\bar{L}_f}x_4 \end{bmatrix} + \Gamma^{-1}(x)\begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} \tag{9}$$

where $\bar{L}_f$ and $\bar{C}_f$ are the nominal values of output filter and capacitor, $\Gamma^{-1}(x)$ is the inversion of Γ which has been defined based on inductor and capacitor reactance, and $v_1(t)$ and $v_2(t)$ are the virtual control inputs which should be designed appropriately.

The same authors in [45] have recently developed the previous concept by making the observer adaptive through a variable design parameter in the observer structure. The weighting matrixes of Riccati's equation have optimally been obtained and also, the flat model of the BILPCs dynamic model has been presented based on flatness concept. In this approach, the following minimization problem must be solved:

$$\|[sI + \ell_2 C[sI - (A - \ell_1 C)]^{-1}N]^{-1}\|_\infty \leq \varepsilon \tag{10}$$

where ℓ_1 and ℓ_2 are high-gains of PI observer which should be determined. More details can be found in [45].

In [70], using an explicit model predictive control concept, an optimal current control strategy has been proposed for interlinking power converters in HMGs. The strategy has protected the BILPC against fault and also provided an optimal power exchange control between AC and DC microgrids in the HMG.

3.2.4. Active Power Sharing Methods

The active power sharing-based methods presented for the BILPCs are classified here as: 1) master-slave, and 2) instantaneous average current sharing (IACS) control strategies. In [71], considering a low-voltage multi-terminal HMG, a master-slave control strategy has been proposed in order to enhance the system stability and maintain reliable operation of power converters. Also, in [72], a control strategy based on master-slave concept has been proposed for BILPCs in an HMG. The proposed control strategy has been able to provide smooth power exchange between AC and DC microgrids.

Moreover, in [73], an optimized master-slave control strategy has been described for optimal operation of BILPC and renewable resources. The particle swarm optimization (PSO) algorithm has been used to optimize the master controller. Recently, considering the IACS concept, parallel-connected Γ-Z-source power converters have been used in [74], to interconnect HMGs and control the power exchange between AC and DC microgrids. The authors have proposed gain-regulating algorithm to make the current controllers of the IACS scheme adaptive as follows:

$$\begin{aligned} &\alpha_1(i+1) = \alpha_1(i) + \theta \\ &\theta = 0 \quad , \quad \text{if} \quad T_1 \leq i_{dn} \leq -T_1 \\ &\theta = -C_1 \; , \quad \text{if} \quad i_{dn} > T_1 \\ &\theta = C_1 \quad , \quad \text{if} \; i_{dn} < -T_1 \end{aligned} \tag{11}$$

where α_1 is the gain, C_1 is the increment in the gain in each step, i_{dn} is the current error (difference of the reference current with BILPC current), and T_1 is the allowable limit for the error.

This has resulted in appropriate power sharing among power converters and also regulated output current.

3.2.5. Instantaneous Power Theory-based Methods

In [43, 46], the operation of parallel-connected BILPCs in an HMG under unbalanced grid voltage has been studied. The authors have used the instantaneous power theory to split power oscillation terms in formulating active and reactive power flow. In order to remove these oscillating terms, a control strategy has been proposed for BILPCs which have been able to provide stable power exchange between the DC and AC sides. To do this, one BILPC has been chosen with higher ratings, called redundant BILPC, which has been used to carry overcurrent caused by faults. In this way, other BILPCs can operate with nominal current. Although the proposed strategy has successfully been able to remove active power oscillations, the reactive power oscillations have not been improved (or even it has worsened) by using this control strategy. The main parameter for BILPC control is the maximum current which is obtained as follows:

$$I_{a/b/c,max} = ((I_L cos\varphi)^2 + (I_S sin\varphi)^2)^{1/2} \tag{12}$$

where I_L and I_S are the lengths of semi-major current axis, and φ is the rotation angle.

Table 6 presents the main advantages and disadvantages/challenges of the BILPCs control methods.

Table 6. The main advantages and disadvantages/challenges of BILPCs control methods

Droop-based	-Simple implementation. -Communication free (when operating without a central controller). -Fast dynamic response. -Capable of removing zero-sequence circulating current among BILPCs. -Operational reliability.	-Limit cycle phenomenon may occur in droop controlled BILPCs which results in instability. -Sub-optimal in various cases used in literature. -Making gains adaptive demands for some more control design challenges.
Intelligent Control	-Flexible control design. -Precise power sharing (for example, in comparison to conventional droop). -Easy implementation algorithms. -Fairly fast and reliable.	-Needing training data (for ANN-based controller). -Optimal selection of the membership functions limits may be a challenge for acceptable operation.
Robust, Observer-based and Optimal Control	-Robust against parameters changes. -Switching control structure (when using SMC-based approaches). -Fault-tolerant.	-Sub-optimal in some cases. -Over-conservative when using some approaches, for example, $H\infty$.
Active Power Sharing	-Near optimal/optimal operation. -Fairly fast dynamics response.	-Low reliability in some cases of master-slave-based approaches. -Output current ripple control challenges. -Weak against parameters changes. -Dependency on the output capacitor current feedback.
Instantaneous Power Theory-based	-Capable of reducing the active power oscillations considerably. -Enabling the HMG to operate under unbalanced faults.	-Unable to reduce reactive power oscillations. -Needs redundant BILPC. -Low reliability during failure in the redundant BILPC.

4. Conclusion

One main element in the realization of the smart grid is the hybrid AC/DC microgrid (HMG), which integrates both AC and DC resources and loads and facilitates the reliable operation of smart grids. This paper comprehensively reviewed the interconnection methods of AC and DC microgrids in HMGs. The BILPCs assigned the lion's share part of the interconnection methods of HMGs in literature. Thus, the control methods of these BILPCs have been classified and reviewed in this work. It was found that the droop-control-based methods have been the mostly used control methods for BILPCs. Future research studies may be focused on the enhancement of the robustness and flexibility of the present control methods or developing new control methods based on switched control concepts. Furthermore, alternative methods, for example, small-scale FACTS, are good choices to interconnect HMGs.

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