Control method for improvement of power quality in single interlinking converter hybrid AC-DC microgrids

Mehdi Baharizadeh\(^1\)\(^2\) | Hamid R. Karshenas\(^2\) | Mohammad S. Golsorkhi Esfahani\(^2\)

\(^1\)Department of Electrical Engineering, Khomeinishahr Branch, Islamic Azad University, Khomeinishahr, Isfahan, Iran
\(^2\)Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran

Correspondence
Mehdi Baharizadeh, Islamic Azad University, Khomeinishahr Branch, Daneshjoo Blvd, Manzarieh, Khomeinishahr, Isfahan, Iran. P.O. Box: 8418148099. Email: baharizadeh@iaukhsh.ac.ir

Abstract
Hybrid AC-DC microgrids (HMGs) are formed by interconnecting AC microgrids (MGs) and DC microgrids via AC-DC interlinking converters (ICs). In the islanded mode, apart from power sharing in a single MG, power sharing expansion throughout HMG is desirable. Conventionally, this is achieved by employing an IC control mechanism in coordination with the droop characteristics of sources. Because the conventional control strategy of IC relies on measuring the frequency variations in AC MG, accurate coordination necessitates a wide range of frequency deviation. Also, this strategy employs the current-controlled method, which fails to accomplish superior voltage quality during load transients and in the presence of an unbalanced load obtainable by the voltage-controlled method (VCM). An IC control strategy for single IC HMGs is proposed that does not require the measurement of frequency variation and employs VCM in the inner control loop. As a consequence, the power quality of AC MG is improved. The proposed control strategy is phase locked-loop-less. In addition, by supporting the related MG with the disconnection of sources in AC MG or DC MG, it provides a uniform control property. Time domain simulations and experimental results are provided to verify the efficacy of the proposed strategy.

1 | INTRODUCTION

A microgrid (MG) is a small-scale electrical system composed of distributed energy resources and loads interconnected through a distribution system [1, 2]. MGs can be connected to the main electrical power systems or operate autonomously [3]. Although MGs were first implemented as AC systems, DC MGs are becoming increasingly popular as a means of integrating DC loads and sources without using additional DC-AC and AC-DC converters in between [4].

AC distribution systems still have an important role in the power system in coming decades. This is the motivation for introducing a hybrid AC-DC MG (HMG), in which AC and DC MG are interconnected via an AC-DC converter called the interlinking converter (IC) [5–7].

In the islanded mode of HMG, the voltage and frequency of the AC MG are controlled through the AC sources whereas the DC MG voltage is controlled by the DC sources [6]. In the islanded mode, power sharing among sources in each MG is required. To attain this goal with no communication link, which establishes the decentralized control method, source droop characteristics have been employed [8]. By interconnecting MGs, active power sharing could be expanded from sources of a single MG to sources throughout HMG. This power management concept, which is called global power sharing (GPS), reduces power stress on the sources and decreases the required reserve capacity as well as variations in the generated power of sources [6, 9, 10].

To realize GPS, the relative frequency drop of AC MG resulting from the droop characteristic of the active power-frequency (P-f) of AC sources and the relative voltage drop of DC MG caused by the droop characteristic of the active power-voltage (P-V) of DC sources must be equal [9]. To attain this goal, the relative frequency and voltage drops are measured and the difference between them is applied to a controller to determine the active power reference of IC. The active power reference is regulated based on the current control method (CCM) [6, 7, 9–13]. This control strategy degrades the power quality of AC MG, as explained subsequently.

Because the IC should sense the frequency drop of AC MG and the voltage drop of DC MG, the frequency variation range for the P-f droop characteristic of AC sources and the
The uniform control strategies of IC for HMGs with single and multiple ICs were presented in Wang et al. [26] and Li et al. [27], respectively. In these strategies, IC could support the related MG even with the disconnection of sources in AC MG or DC MG. In addition, it is not necessary for IC to detect this disconnection or change its control structure. To provide this property, IC should employ a VCM. In addition, by its power management, IC should support supply-demand unbalance of 1 MG through other. This power support can be provided by equating the relative frequency drop in the AC MG and the relative voltage drop in the DC MG. For this purpose, in Wang et al. [26] and Li et al. [27] the reference value of active power exchange is determined using the measured frequency and voltage drops. Moreover, similar to the AC source control strategy, a P-f droop characteristic has been considered for the IC. To reach the reference power, again an external power control loop is employed. This power loop indicates the vertical shift of the P-f droop characteristic of the IC. However, in addition to increasing the complexity, such extra loops could result in a reduction the speed of the dynamic response. In Zhang et al. [28], a dual-droop characteristic of the IC was introduced in which the reference voltage and frequency of the IC were determined to realize GPS. In that work, these reference values were realized by a data-driven, model-free adaptive VCM. In the strategies proposed elsewhere [22, 23, 25–28], although the IC participated in voltage control of the AC MG through VCM, frequency measurement was required and was performed by a phase locked-loop (PLL).

PLL is commonly used in IC control schemes to extract the frequency of AC MGs [6, 7, 9–12]. The output of PLL is subsequently used as an input for the power control of IC. Thus, the PLL dynamics has a considerable impact on the closed-loop dynamics of the system. In particular, the delay induced by the PLL dynamics can have a detrimental effect on the system stability. To avoid this issue, PLL-less control schemes have been proposed for grid-connected voltage source converters [29, 30]. In Baharizadeh et al. [14], a control strategy of IC with active power-frequency-DC voltage droop characteristics was proposed. This strategy could share the active power exchange between multiple ICs in the HMG. In this VCM-based strategy, measuring the AC MG frequency and hence a PLL is not required. Apart from its complicated droop characteristic, this method has a large power sharing error in single IC HMGs. In Yang et al. [31], a voltage-angle droop control method is proposed for proportional active power sharing among multiple ICs. This method favours zero frequency deviation and a uniform property. However, this scheme requires a communication infrastructure to synchronize ICs and AC sources and does not provide GPS.

A decentralised control strategy for IC in single IC HMGs is proposed. In this strategy, the reference frequency of IC is determined based on the measured voltage drop of DC MG such that GPS is realized. Furthermore, the generated reactive power is applied to a droop characteristic to extract the reference amplitude of voltage. These extracted reference values are realized through a VCM that employs PR controllers. The key features of the proposed method compared with...
the existing solutions are presented in Table 1. In proposed method:

- In contrast with other methods [9, 10, 12, 22, 25–28], the proposed strategy does not require frequency measurement by PLL. Thus, the frequency variation range in AC MG could be chosen to be small, which corresponds to low-frequency deviations. In addition, by eliminating the delay associated with the PLL dynamics, the proposed scheme avoids related stability issues.
- The adaptation of VCM in the inner control loop of the proposed method provides a superior voltage quality in the AC MG (especially within the vicinity of the IC) compared with CCM-based schemes. In particular, transient voltage deviations and voltage unbalance are reduced in the proposed scheme.
- Compared with existing VCM-based control approaches [22, 23, 26, 27], which use multiple cascaded control loops, the proposed method is simpler and favours an enhanced dynamic response.
- The proposed control strategy provides uniform control property. Thus, even with disconnected sources in an AC MG or DC MG, HMG loads could be properly supplied.

The remainder of this paper is organised as follows. In Section 2, the sources control strategy in AC MGs and DC MGs is described. Detailed explanations of problems associated with the conventional control strategy of ICs are presented in Section 3. A proposed control strategy of IC is presented in Section 4. Simulation results are given in Section 5 to validate the proposed control strategy and compare it comprehensively with the conventional strategy. The experimental results obtained with the proposed control strategy are presented in Section 6.

2 SOURCES CONTROL STRATEGY IN AC MICROGRIDS AND DC MICROGRIDS

The decentralised control method employs sources droop characteristics to achieve power sharing in the islanded operation mode [8, 10].

The droop characteristics of AC sources, including active P-f and reactive power-voltage (Q-V) are given in Equations (1) and (2), respectively:

$$f_i^* = f_{\text{max}} - m_{ac,i} P_{ac,i} \quad (1)$$

$$V_{ac,i}^* = V_{ac,\text{max}} - n_{ac,i} Q_{ac,i} \quad (2)$$

where $f_{\text{max}}$ and $V_{ac,\text{max}}$ are the maximum frequency and amplitude of voltage in an AC MG, $f_i^*$ and $V_{ac,i}^*$ are the reference frequency and amplitude of output voltage, $P_{ac,i}$ and $Q_{ac,i}$ are low-pass filtered active and reactive powers and $m_{ac,i}$ and $n_{ac,i}$ are slopes of P-f and Q-V droops in an ith AC source, respectively. The transfer function of low-pass filters (LPFs) considered is:

$$LPF(s) = \frac{\omega_c}{s + \omega_c} \quad (3)$$

where $\omega_c$ is the cut-off frequency. $m_{ac,i}$ is calculated as the ratio of the intended frequency variation range in the AC MG to the rated source active power and $n_{ac,i}$ is calculated as the ratio of intended voltage variation range in the AC MG to the rated source reactive power. This results in active and reactive power sharing between AC sources, in accordance with the rated sources power [8, 10]. It is supposed that the lines of the AC MG are dominantly inductive. However, in case of dominantly resistive lines, instead of P-f and Q-V droop characteristics, AC sources could employ P-V and Q-f characteristics [32].

The reference voltage obtained by the droop characteristics is tracked by the voltage controller. Employing VCM in the AC sources enables them to contribute to voltage and frequency control of the AC MG. The VCM is composed of the external voltage control loop and the internal current control loop realized in the $\alpha\beta$ orthogonal frame. These loops employ the PR controllers:

$$PR(s) = k_p + \frac{2k_r \omega_c s}{s^2 + 2\omega_c s + \omega_c^2} \quad (4)$$

where $k_p$ is the proportional gain, $k_r$ is the resonant gain, $\omega_c$ is the angular frequency and $\omega_c$ is the cut-off bandwidth.

The P-V droop characteristic employed in the DC sources is given by:

$$V_{dc,i}^* = V_{dc,\text{max}} - m_{dc,i} P_{dc,i} \quad (5)$$

where $V_{dc,\text{max}}$ is the intended maximum voltage in the DC MG, $V_{dc,i}^*$ is the reference value of output voltage, $P_{dc,i}$ is the filtered generated active power and $m_{dc,i}$ is the droop slope in the ith DC source. $m_{dc,i}$ is calculated as the ratio of the intended voltage variation range in the DC MG to the rated source power. The output reference voltage of the DC source is controlled based on the VCM [4, 10].

3 PROBLEM STATEMENT

In the AC MG, where the frequency is controlled by the P-f droop characteristic, an increase in active power loading of AC sources is followed by a frequency drop. The per-unit frequency drop of AC MG is defined by Equation (6):

$$\Delta f_{pu} = \frac{f_{\text{max}} - f}{f_{\text{max}} - f_{\text{min}}} \quad (6)$$

where $f_{\text{min}}$ and $f_{\text{max}}$ are the minimum and maximum frequencies, which occur at zero and rated active power loading conditions, respectively. As the active power loading of AC sources changes between 0% and 100%, the frequency changes from $f_{\text{max}}$ to $f_{\text{min}}$ and the per-unit frequency drop changes
between zero and one. Therefore, the per-unit frequency drop is equal to relative active power loading of the AC sources. In the DC MG, an increase in power loading of DC sources is followed by a voltage drop. Similarly, the per-unit voltage drop of DC MG, which indicates the relative power loading of the DC sources, is defined by Equation (7):

$$\Delta v_{dc,\text{pu}} = \frac{V_{dc,max} - V_{dc}}{V_{dc,max} - V_{dc,min}}$$

(7)

where $V_{dc,min}$ is the minimum voltage in the DC MG. To satisfy the GPS, the relative active power loading of AC sources should be equal to the relative active power loading of the DC sources. Therefore, equating the per-unit frequency drop of the AC MG and the per-unit voltage drop of the DC MG is considered a method for realizing the GPS. The IC controller is responsible for equating these per-unit values [6, 9–14].

The topology of the IC in an HMG is shown in Figure 1a. In other work [6, 7, 9–13], the IC measured the AC bus frequency, denoted by $f_{ic}$, and the DC bus voltage, denoted by $v_{dc,ic}$; the corresponding per-unit drop values were extracted in accordance with Equations (6) and (7). Then, the difference was applied to a proportional-integral (PI) controller to determine the reference value of active power exchange. The PI controller adjusts the IC reference power such that the per-unit frequency drop of IC AC bus ($\Delta f_{ic,pu}$) and the per-unit voltage drop of IC DC bus ($\Delta v_{dc,ic,pu}$) become equal:

$$P_{ic}^* = k_p \left( \Delta v_{dc,ic,pu} - \Delta f_{ic,pu} \right) + k_i \int \left( \Delta v_{dc,ic,pu} - \Delta f_{ic,pu} \right) dt$$

(8)

where $P_{ic}^*$ is the reference active power of IC injected to an AC MG and $k_p$ and $k_i$ are the proportional and integral gains of the PI controller.

The IC participates in the reactive power generation of the AC MG by defining the reference reactive power:

$$Q_{ic}^* = n_{ac,ic}^{-1} \left( V_{ac,\text{max}} - V_{ac,ic} \right)$$

(9)

where $V_{ac,ic}$ is the filtered voltage amplitude of the IC AC bus, $Q_{ic}^*$ is the reference reactive power injected to the AC MG and $n_{ac,ic}$ is the droop slope, which is inversely proportional to the rated reactive power of the IC.

The output reference current of the IC denoted by $i_{ac,ic}^*$ is derived as:

$$i_{ac,ic,d}^* = \frac{3}{2} \frac{P_{ic}^*}{v_{ac,ic,d}}, i_{ac,ic,q}^* = \frac{3}{2} \frac{Q_{ic}^*}{v_{ac,ic,q}}$$

(10)

where subscripts $d$ and $q$ represent values in $d$ and $q$-axis of the synchronous rotating frame. The $d$-axis is chosen to have a
FIGURE 1 (a) Interlinking converter (IC) topology; (b) Conventional control strategy of IC. CCM, current-controlled method; MG, microgrid; PI, proportional-integral; PLL, phase locked-loop

90-degree lead with respect to the \( q \)-axis. In addition, for each AC converter, the \( d \)-axis is aligned to the voltage space vector of its AC terminal. To track the reference current, the CCM is employed \([6, 9–12]\). The CCM is composed of two internal and external current control loops in the \( \alpha \beta \) orthogonal frame with the PR controllers \([33]\). This control strategy is shown in Figure 1b. The IC conventional control strategy is based on the extracted per-unit frequency drop of the AC MG and per-unit voltage drop of the DC MG. Extracting valid per-unit drop values may be difficult owing to the presence of noise \([9, 14]\).

Consider Equation (11), which describes the measured IC AC bus frequency:

\[
\Delta f_{ic} = \bar{f} + \tilde{f}
\]

where \( \bar{f} \) is the ideal component related to the relative active power loading of the AC sources. The difference between the measured frequency and the ideal component \( \bar{f} \) is caused by measurement error, the PLL performance, and the resulting phase shift. Different working conditions for sensors may cause steady-state error in the measured frequency. Transient frequency measurement error arises as a result of the PLL dynamics. In addition, intense frequency variations, which are not related to the active power of the AC sources, may be developed owing to phase shift phenomenon. By substituting Equation (11) in Equation (6), the per-unit frequency drop of IC AC bus is extracted as:

\[
\Delta f_{pu} = \Delta f_{pu}^{\bar{f}} + \frac{-\tilde{f}}{f_{\text{max}} - f_{\text{min}}}
\]

in which \( \Delta f_{pu}^{\bar{f}} = (f_{\text{max}} - \bar{f}) / (f_{\text{max}} - f_{\text{min}}) \) is equal to the relative active power loading of the AC sources. In the conventional control strategy, \( \Delta f_{pu}^{\bar{f}} \) is used to determine the reference active power of IC (Equation 8). Therefore, the second term on the right hand side of Equation (12) causes the active power of the IC to deviate from its intended value. Such a deviation causes inaccurate power sharing among DC and AC sources and may lead to system instability. To circumvent this issue, the magnitude of this term can be decreased by choosing a relatively large value for the frequency variation range \( f_{\text{max}} - f_{\text{min}} \). Because a large frequency variation range is not necessary in AC MGs that are not a part of a HMG, this large variation range is an extra problem imposed on the HMG by the conventional control strategy of the IC.

Employing CCM by the conventional strategy could result in the poor voltage quality of AC MGs. The CCM employed in the IC inner control level does not provide voltage control. Based on Equation (9), by generating reactive power and subsequently interacting with AC sources, IC tries to preserve the voltage level within the desired level. However, this operation is implemented in the outer control level of power management, which is relatively slow. Thus, the conventional strategy during AC load transients could result in a voltage drop or a rise in the IC AC bus and the AC buses close to the IC. In contrast, by using VCM in the inner control level, voltage support can be provided during transients. In addition, CCM does not provide minor impedance in negative sequence whereas the VCM that employs PR controllers does \([21]\). Consequently, in the presence of unbalanced loads, the conventional strategy might suffer from severe voltage unbalance in IC AC bus and the AC buses close to IC. Moreover, as shown in Figure 1b, the conventional method uses the frequency and angle of the voltage space vector as inputs. Because these parameters are extracted by the PLL, the PLL has a key role in this strategy. Thus, the PLL dynamics can adversely affect stability, particularly in weak grids operated in the islanded mode \([29, 30]\).
4 PROPOSED CONTROL STRATEGY OF INTERLINKING CONVERTER

This section presents a control strategy for ICs. The strategy employs VCM and does not require extraction of the AC MG per-unit frequency drop. In this strategy, the IC DC bus voltage is measured and the corresponding per-unit voltage drop is extracted based on Equation (7). To ensure GPS, the reference per-unit frequency drop of the IC AC bus must be equal to the per-unit voltage drop of IC DC bus. To that end, the reference frequency of IC AC bus is calculated as:

\[ f_{ic}^* = f_{max} - \Delta V_{dc,ic,pu} \cdot (f_{max} - f_{min}) \]  

(13)

where \( \Delta V_{dc,ic,pu} \) is the filtered per-unit voltage drop of the IC DC bus. If the DC MG load is increased, the power generation of the DC sources will be increased. This leads to a decrease in the DC MG voltage because of the reaction of the P-V droop characteristic of the DC sources. According to Equation (13), the reference frequency of IC AC bus is reduced. As a result, the P-f droop characteristic reaction of the AC sources increases active power generation to achieve GPS. On the other hand, if the load in the AC MG is increased, its active power is initially supplied by the IC. This extra power is supplied from the DC sources. Accordingly, the DC MG voltage is reduced owing to the droop characteristic reaction of the sources. According to Equation (13), the AC MG frequency will drop and the AC sources power will increase to realize GPS.

For IC participation in reactive power generation, unlike the conventional strategy, the reference voltage of IC AC bus is extracted by measuring the IC generated reactive power. Thus, the droop characteristic that is similar to AC sources is used:

\[ V_{ac,ic}^* = V_{ac,max} - n_{ac,ic} \cdot Q_{ic} \]  

(14)

where \( V_{ac,ic}^* \) is the reference amplitude of the IC AC bus voltage and \( Q_{ic} \) is the filtered generated reactive power.

### TABLE 2 Parameters of the test HMG

| AC line 1 | \( R = 0.5 \, \Omega, \, L = 3 \, mH \) |
|-----------|--------------------------------------|
| AC line 2 | \( R = 0.5 \, \Omega, \, L = 3 \, mH \) |
| AC Source1 | \( P_{rated} = 15 \, kW, \, Q_{rated} = 7.5 \, kVAR, \, V_{ac,max} = 310.3 \, V, \, V_{ac,min} = 279.2 \, V, \, \text{Outer PR:} \, kp = 2, \, kr = 100, \, \omega_s = 6, \, \text{Inner PR:} \, kp = 10, \, kr = 1000, \, \omega_s = 6 \) |
| DC line 1 | \( R = 0.25 \, \Omega, \, L = 0.25 \, mH \) |
| DC line 2 | \( R = 0.25 \, \Omega, \, L = 0.25 \, mH \) |
| DC Source1 | \( P_{rated} = 15 \, kW, \, V_{dc,max} = 750 \, V, \, V_{dc,min} = 675 \, V, \, \text{Outer PI:} \, kp = 0.2, \, kr = 100, \, \text{Inner PI:} \, kp = 50, \, ki = 300000 \) |
| IC | \( P_{rated} = 15 \, kW, \, Q_{rated} = 7.5 \, kVAR, \, \text{Outer PR:} \, kp = 2, \, kr = 100, \, \omega_s = 6, \, \text{Inner PR:} \, kp = 10, \, kr = 1000, \, \omega_s = 6, \, \text{Conventional control strategy:} \, f_{max} = 51 \, Hz, \, f_{min} = 49 \, Hz, \, \text{Proposed control strategy:} \, f_{max} = 50.1 \, Hz, \, f_{min} = 49.9 \, Hz \) |
| LPFs | \( \text{First-order, cut-off frequency = 31.4 \, rad/s} \) |

Abbreviations: HMG, hybrid AC-DC microgrid; LPF, low-pass filter; PI, proportional-integral; PR, proportional-resonance.
After determining the reference frequency and the reference amplitude of IC AC bus voltage according to Equations (13) and (14), these reference values are realized through the VCM. The proposed control structure is shown in Figure 2. By measuring the IC DC bus voltage, and based on the method explained in the beginning of this section, the reference frequency of the IC AC bus is calculated. Then, by integration, the reference angle of the voltage space vector of the IC AC bus is extracted. Furthermore, the generated reactive power is calculated based on the measured AC voltage and current, and applied to the droop characteristic to extract the reference amplitude of the IC AC bus voltage, which is equal to the reference magnitude of the voltage space vector of the IC AC bus. These extracted reference values are realized through VCM. The VCM is composed of the external voltage control loop and the internal current control loop, which are realized in the αβ orthogonal frame. In this strategy, the frequency measurement and per-unit frequency drop extraction are not required. Thus, the frequency variation range can be decreased compared with the conventional method. By using the VCM, the IC participates in voltage control of the AC MG. This improves the AC MG voltage quality. Moreover, because measurement of the frequency and magnitude and

**Figure 4** Simulation results of test hybrid AC-DC microgrid (MG) with conventional control strategy: (a) Measured per-unit frequency drop of interlinking converter (IC) AC bus and per-unit voltage drop of IC DC bus, (b) Generated active power of sources and exchanged active power of IC, (c) Generated reactive power of AC source and IC, (d) Frequency of AC MG.
angle of voltage space vector of the IC AC bus is not required in the proposed control strategy, it could operate PLL-less.

Although the focus is on HMG power quality improvement, the proposed control strategy also features uniform control property, which means that IC is able to support the AC MG or DC MG even under the condition of disconnecting of their corresponding sources [26, 27]. Based on the proposed strategy, the AC MG voltage and frequency can be controlled through the VCM in the IC. Therefore, the AC MG can be stabilised during disconnection of the AC sources. Moreover, the voltage amplitude of AC MG is regulated within the intended range based on Equation (14). The frequency is regulated within the intended range because, based on Equation (13), the frequency is related to the DC MG voltage properly regulated by the P-V droop characteristic of DC sources. If the DC sources are disconnected from the DC MG, its voltage will be decreased. This leads to the decrease in AC MG frequency in accordance with Equation (13). Then, the active power generation of the AC sources is increased. The generated extra power is applied to the DC MG through the IC to establish a balance between generation and consumption.

**FIGURE 5** Simulation results of the test hybrid AC-DC microgrid (MG) with proposed control strategy. (a) Measured per-unit frequency drop of interlinking converter (IC) AC bus and per-unit voltage drop of IC DC bus. (b) Generated active power of sources and exchanged active power of IC. (c) Generated reactive power of AC source and IC. (d) Frequency of AC MG.
and ensure DC MG stability. Moreover, by satisfying Equation (13), the DC MG voltage related to the AC MG frequency, properly regulated by the P-f droop characteristic of AC sources, is regulated within the intended range.

Although the lines in AC MGs are assumed to be dominantly inductive, the proposed method can be extended to purely (or dominantly) resistive networks. In such a case, the AC sources employ P-V and Q-f droop characteristics
instead of P-f and Q-V droop schemes. Thus, the per-unit voltage and frequency deviations of AC MGs indicate the active and reactive power loading of the AC sources, respectively. To comply with this condition, the AC voltage and frequency should be swapped in the proposed IC control scheme. Specifically, the reference of the IC AC bus voltage should be calculated based on the measured DC MG voltage and the reference frequency should be calculated based on the measured reactive power of the IC. In this case, because the reference frequency is calculated and realized by the VCM, it is not required to measure the frequency drop by the PLL, similar to the dominantly inductive lines case.

5 | SIMULATION RESULTS

In this section, time-domain simulations in diverse conditions are used to verify the performance of the proposed strategy and compare it with the conventional method. Figure 3 shows the single line diagram of the simulated HMG. The parameters of this HMG are presented in Table 2.

In the first study, initially AC load 1 draws 7 kW and 2.1 kVAR and DC load 1 draws 3 kW. At \( t = 3 \) s, DC load 1 is increased to 10 kW. Then, AC load 1 is increased to 14 kW and 7 kVAR at \( t = 6 \) s. This step AC load decreases at \( t = 9 \) s. Simulation results for the conventional and proposed strategies of IC are shown in Figures 4 and 5, respectively. As can be seen
in Figures 4a and 5a, both strategies ensure GPS by equalising the per-unit frequency of the IC AC bus and the per-unit voltage of the IC DC bus. Active power generation of sources and active power exchange of the IC are shown in Figures 4b and 5b. When either the DC or AC loads are increased, both the DC and AC sources contribute to pick...
up the rise in the load by increasing their power generation. As expected, by decreasing the AC load, the power generation of both DC and AC sources are decreased. The participation of IC in reactive power generation is shown in Figures 4c and 5c.

Figures 4b, c and 5b, c confirm that the proposed and conventional strategies are similar in performance from a power management point of view. Whereas the proposed strategy maintains a frequency within 49.9–50.1 Hz, the frequency deviations in the case of the conventional method exceeds the permissible range of ±0.1 Hz suggested by power quality standards [16].

In another study, a 10-kW resistive load in the IC AC bus (AC load 2) is connected at $t = 0.8$ s whereas the AC load 1 as a constant load draws 8.2 kW and 4 kVAR. The space vector magnitude of voltages in the AC MG that are equal to the amplitude of phase voltages in it is considered in this part. Related simulation results with the conventional and proposed strategies of ICs are shown in Figure 6. By using the conventional strategy, when the load changes, a transient voltage drop occurs in the AC MG. This voltage drop is severe in the IC AC bus, and this severity decreases while close to the AC source. Using the proposed strategy, the transient voltage drop is properly limited. This improvement is prominent in buses close to the IC, as the result of employing the VCM in the IC.

To study unbalance, AC load 2 as a line-to-line, single-phase, 7-kW resistive load is connected with AC load 1 as a three-phase load drawing 4.8 kW and 2.3 kVAR. Phase voltages of AC MG buses are shown in Figures 7 and 8, which respectively correspond to the conventional and proposed strategies. In addition, voltage unbalance factors (VUFs) are calculated and presented in Table 3. The VUF is defined as:
\[ VUF = \frac{V_{ac}^+ + V_{ac}^-}{V_{ac}} \times 100 \]  

(15)

where \( V_{ac}^+ \) and \( V_{ac}^- \) are the positive sequence amplitude and negative sequence amplitude of bus voltages. By using the conventional strategy, the VUF in the IC AC bus is as big as 10.7\% whereas the smaller VUF values are obtained by being close to the AC source. Using the proposed strategy, the voltage quality in the IC AC bus is considerably improved and the VUF reaches 1.34\%. The VUF at the other buses of the AC MG also are decreased compared with the case in which the conventional method is used; however, the improvement is stronger at the AC buses closer to the IC.

To verify the uniform control property of the proposed control strategy of the IC, disconnection of the AC source and the DC source is studied. In these studies, the AC load 1 draws 2.5 kW and 0.75 kVAR and DC load 1 draws 10 kW.

Results corresponding to the disconnection of AC source at \( t = 1 \) s are shown in Figure 9. As can be seen in Figure 9a, by disconnecting the AC source, the active power of the DC source is increased to supply both the AC and DC loads, which becomes feasible by means of the proper active power exchange of IC.

**FIGURE 13** Experimental results of the test hybrid AC-DC microgrid (MG) with proposed control strategy. (a) Measured per-unit frequency drop of interlinking converter (IC) AC bus and per-unit voltage drop of IC DC bus. (b) Generated active power of sources and exchanged active power of IC. (c) Generated reactive power of AC source and IC. (d) Frequency of AC MG.
The voltage amplitude and frequency of AC MG are shown in Figure 9(b) and (c). The AC MG is stabilised whereas its voltage results corresponding to the disconnection of the DC source at \( t = 1 \) s are shown in Figure 10. Figure 10(a) shows that by disconnecting the DC source, the active power of the AC source is increased to supply both the AC and DC loads. The voltage of the DC MG is shown in Figure 10(d). The DC MG is stabilised whereas its voltage is regulated within the intended range.

amplitude and frequency are regulated within the intended range

To show that the proposed control strategy of IC does not disrupt the coordination of multiple sources in each MG, AC source 2 and DC source 2 are added to the test HMG in Figure 3. AC source 2 is connected to the AC node through AC line 3 and DC source 2 is connected to the DC node through DC line 3. The parameters of the added elements are presented in Table 4. The load variation scenario is similar to the first study. The simulation results are shown in Figure 11. By increasing the DC load at \( t = 3 \) s and the AC load at \( t = 6 \) s, active power generation of both DC sources and both AC sources are increased. This operation is based on the realization of active power sharing between DC sources, active power sharing between AC sources and GPS. In addition, by increasing the AC load at \( t = 6 \) s, reactive power generation of both AC sources and IC is increased, based on the realization of reactive power sharing between AC sources and reactive power sharing between AC sources and IC.

6 | EXPERIMENTAL RESULTS

To verify the efficacy of the proposed strategy in practice, the test HMG of Figure 3 is implemented using an experimental MG in the MG Laboratory of the University of Hong Kong. The simulation benchmark is matched with the experimental setup to enable the results to be compared. As shown in Figure 12, the experimental setup is composed of three interconnected cabinets, each of which includes five 15-kW converters and associated LCL filters (Figure 12[b]). In each cabinet, two converters are front-end rectifiers that supply the DC bus of three inverters. The AC source and IC are implemented using two inverters. Furthermore, the AC load is implemented using two inverters, the reference currents of which are controlled according to the load active power and PF set points. The DC MG is emulated using real-time simulations.

To facilitate implementation of the control strategy, a PC and FPGA-based control architecture is used. The control system is first modelled in MATLAB and then compiled to C++ code using a real-time coder toolbox. Then, the code is transferred to the target PCs, which calculate the control command (PWM reference signals for inverters) based on feedback signals from the hardware. The control command is then transferred to the FPGA boards of the inverters by fibre-optic cables.

The experimental results are shown in Figure 13. The load variation scenario is similar to the first study in simulation results. When the DC load is increased at \( t = 3 \) s, the P-V droop characteristic of the DC source responds to this load increase by decreasing the DC bus voltage. Consequently, the power flow through the IC becomes reversed (energy flows from AC to DC) to ensure the load is evenly shared among the sources in the AC and DC MGs. Furthermore, the AC load step at \( t = 6 \) s triggers a frequency drop in the AC MG, which causes the active power of IC to be reversed again. In addition, the reactive power controller of the IC adjusts the reactive power output so that the AC load reactive power is shared among IC and AC sources. The step AC load decrease at \( t = 9 \) s causes the parameters to change back to their previous values. Moreover, frequency deviations are less than 0.1 Hz. A comparison of experimental results (Figure 13) with simulations (Figure 5) validates the simulations and showcases the efficacy of the proposed method in practice.

7 | CONCLUSION

A control strategy is proposed for HMGs with a single IC to realize GPS. Unlike the conventional control method, the proposed strategy does not require the AC MG frequency to be measured. Therefore, the required range of frequency deviation can be decreased to within the permissible range suggested by IEEE Standard 1159 [15]. Moreover, employing VCM by the IC improves the voltage quality of the AC MG. In addition to an improvement in power quality, the proposed strategy provides uniform control. Simulation results show that the proposed strategy effectively limits frequency deviation. Moreover, the transient voltage drop owing to load change as well as VUF in the presence of an unbalance loads are significantly decreased. Both of these improvements are more evident in AC buses close to the IC. In addition to the simulations, the method was tested experimentally using a laboratory benchmark MG at the University of Hong Kong. The experimental results showcase the efficacy of the proposed method in practice.

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