Realising a system of coupled microgrid networks using single-phase interconnection lines

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Abstract
Overloading and renewable-based excessive generation are a frequently observed phenomena in an autonomously operating islanded microgrid (MG) which will lead to unacceptable voltage or frequency deviation in the MG. Such problems can be alleviated by mechanisms such as load shedding or curtailment of renewable sources. Alternatively, coupling the neighbouring MGs and enabling a provisional power exchange amongst them can improve the situation more effectively. The power exchange link between the MGs can be in the form of a conventional three-phase ac line but a single-phase ac line is more cost-effective, especially considering the amount of the power that needs to be transferred through this link. This approach requires power electronics-based converters to convert a three-phase ac MG into a single-phase power exchange link and control the power sharing amongst them. The same is needed when the MGs have to be coupled while maintaining their autonomy, but the corresponding costs of the single-phase system are less. This article has proposed a decentralised approach to control and couple the neighbouring MGs to realise provisional power exchange through such a structure. The performance of the proposed control mechanism is evaluated through simulation studies in PSIM®, and its sensitivity and stability are analysed against its key design and operational factors.

1 | INTRODUCTION

Microgrids (MGs) are small clusters of distributed generators (DGs) and loads, which can operate under a centralised or decentralised control approach [1–3]. In addition, MGs can operate in two different modes, namely autonomous (islanded) and grid connected. In the autonomous mode, one or more of the DGs usually operate under the droop control to realise the desired power sharing amongst them while regulating the desired voltage and frequency in the system [4]. Nowadays, the utilities of remote areas prefer to operate their edge-of-the-grid or regional networks in the form of MGs and supply the local loads by integrating a large number of renewable sources. Studies have demonstrated that such projects significantly reduce the levelised cost of energy [5,6]. Thus, the trend of standalone MGs is becoming prominent in remote off-grid towns. Such MGs’ power supply will be dominated by renewable energy sources along with diesel/gas-driven synchronous generators [7].

1.1 | Motivation

Due to high intermittency associated with renewable energy resources, the probability of observing overloading or excessive generation from the renewable-based DGs in such standalone MGs is very high [8]. The term overload refers to the temporary deficit in the MG's generation capacity compared to its gross demand. On the other hand, excessive generation refers to the situation when an MG experiences a large generation of power through one or more of its non-dispatchable, renewable-based DGs without a proper load to consume it at that time. Load shedding is the simplest approach to address the first problem and return the voltage and frequency to the acceptable limits. For the latter, the corresponding renewable energy sources can be curtailed as a solution. However, such solutions are undesirable and uneconomic. Alternatively, energy storage systems can alleviate these problems and the corresponding voltage and frequency issues but impose extra costs [8,9].
1.2 | Literature review

To address the above problems more effectively, a third approach is proposed in [10–12], i.e. temporarily interconnecting the neighbouring MGs to each other during such conditions to exchange power amongst them. Studies of [13–15] have illustrated that the issues of overloading or excess generation can be realised by properly interconnecting two or more of the neighbouring MGs and the frequency and voltage can then be retained within the acceptable limits and the system stability will be improved. Such an arrangement of interconnected autonomous MGs is referred to as a system of coupled microgrids (CMGs) in the remaining article. Lasseter [3] has discussed the CMG model and its operation based on the availability of communication infrastructure and the concept of the power market. An extensive analysis of different CMG architectures is shown in detail in [16,17]. Sharing load demands through an interactive control of CMG for wide system stability is shown in [18,19]. The existing literature on CMG is mostly focused on system-level studies, such as stability analysis, energy management, demand response and economic evaluation [5,6,16]. In the majority of these studies, the key assumption is the coupling of MGs through direct ac lines.

The physical interconnecting link can be based on a three-phase line through conventional circuit breakers or static switches [20]. However, each MG may have a different operator, and thus, their operational and control structure and standards can be different from each other and may also depend on the local DGs in the MGs. Therefore, for such situations, proper isolation must be provided among the MGs instead of directly coupling them via three-phase ac lines and conventional circuit breakers [10–12,21,22] so that every MG can operate independently and autonomously while exchanging power with each other. Therefore, a back-to-back power electronics-based converter is a good candidate for the physical interconnecting link in such conditions to enable proper isolation while facilitating power exchange. Dynamic power sharing between two islanded MGs connected through three-phase back-to-back converters is studied in [11,13,22]. An appropriate electrical framework and protocol along with a specific power exchange strategy [20] are also needed to exchange power through an interconnected system of MGs.

1.3 | Contribution and organisation

This paper has suggested employing a single-phase ac line instead of a three-phase ac line for the interconnecting link of CMGs. Since the interconnecting link is operational only during the contingency of overloading or overgeneration, the amount of power exchanged through the link is not very large (around 10%–20% of an MG’s maximum capacity). Thus, employing a single-phase link instead of a three-phase one would be more economical because of the reduced number of lines, power electronic converters and filters. If so, the back-to-back connected converter must enable the connection of a three-phase MG to a single-phase ac line. This is shown schematically in Figure 1(a) while Figure 1(b) shows the topology of the assumed back-to-back converter. Such an interconnecting link can also be realised with dc systems too, but the majority of the power line infrastructure and commercially available equipment are based on ac systems. At the same time, the network operators are generally more familiar with ac systems compared to dc systems. Moreover, the protection schemes and equipment for ac systems are cheaper than dc systems.

To enable the operation of such a system, this paper has proposed a suitable power exchange strategy between the MGs within the CMG along with the appropriate structure and control principles for the power electronic converters. The proposed approach is general and applicable to couple N autonomous MGs for exchanging power amongst them. The proposed approach does not need any communication between the MGs and solely operates based on local measurements at either side of the converters, thus providing an extra benefit by reducing the necessity and cost of a communication system. The back-to-back connection of the converter provides isolation between the MGs and ensures the autonomy in the operation of each MG, and thus, enables them to operate at any voltage and frequency level and operational standards. The proposed scheme enables the single-phase link to exchange power autonomously during overloading/overgeneration in an MG without the need for any communication among the MGs. Thus, it will enhance the resiliency and self-healing capability of each MG.

The performance of the proposed mechanism and control strategy are evaluated through extensive computer-based simulation studies using PSIM®. Finally, the sensitivity of the proposal is validated against the key design and operational factors to demonstrate its robustness.

In summary, the main contributions of this paper to the research field are as follows:

- Proposing a single-phase link to realise power exchange amongst the neighbouring isolated MGs to alleviate overloading/overgeneration situations and to retain the desired voltage and frequency level and system stability.
- Developing a decentralised control approach to facilitate power exchange among the MGs, which is scalable to couple any number of MGs with different voltage and frequencies.

The rest of the article is organised as follows: Section 2 discusses the proposed power exchange strategy while the considered power electronic converter structure and control under different modes of operation are introduced in Section 3. Section 4 provides a brief comparison of the proposed single-phase link and the conventional three-phase one. The performance of the proposed power exchange strategy is evaluated and demonstrated through several case studies in Section 5. The sensitivity and stability of the proposed approach are respectively discussed in Sections 6 and 7. Section 8 discusses the study outcomes in detail and provides an
overall discussion of the obtained results. Finally, the key findings of the research are summarised and highlighted. Three appendices at the end of the paper introduce the assumed MG operation in each MG, the technical data considered in the numerical studies of the paper and tabulated data for sensitivity analysis.

2 | PROPOSED POWER EXCHANGE STRATEGY

The CMG is formed by the neighbouring MGs through back-to-back power electronics converters and a single-phase ac interconnecting power line. The converter connected to the MG is labelled as the MG-side converter (MSC), while the other one is labelled as the line-side converter (LSC). Both MSC and LSC are voltage source converters (VSCs) are connected to and isolated from each other via a common dc link, which enables the MGs to operate with full autonomy and no synchronisation of MSC to LSC is required.

Enabling the power exchange among the MGs during an overloading/excess generation can be realised by monitoring the frequency of individual MGs. As the load demand of an MG increases, its frequency decreases, and vice versa. This behaviour can be used as an indication for the MG's power shortage or surplus, and thus, the need for any communication links or a centralised controller is eliminated. This benefits the operators of such systems by saving costs in installing and operating communication infrastructure for this purpose only. It is to be noted that, even in the presence of a central controller and communication links for the same purpose, the proposed approach can be employed as the backup system is activated in the event of communication failure or during any contingency.

Under the above framework, the MGs are allowed to participate in forming the CMG based on a predefined guideline, as allowing all (or a large number of) MGs to be included in the CMG may lead to system instability. To this end, the formation of a CMG would be allowed or denied based on the MGs’ existing loading level, which is identified by measuring their frequencies in this study. In this regard, every MG is classified and flagged in either of the three categories of a healthy, problem or floating MG (denoted by HMG, PMG and FMG, respectively), as mentioned below:

- An HMG refers to the state when an MG is operating within its nominal voltage and frequency range and can support the other neighbouring MGs by exchanging power.
- A PMG is referred to as an operating condition in which the MG experiences overloading or excess generation. PMGs are expected to connect to one or more neighbouring HMGs and exchange power to retain their voltage and frequency within the acceptable limits.
- An FMG is referred to as a loading condition that is in the boundary of becoming a PMG. In other words, the MG's voltage or frequency is very close to the maximum or minimum acceptable limits, and hence, should not be allowed to help other PMGs.

To better understand the performance of such a system, let us assume that $f_{\text{MG}}$ is the operating frequency of the MG, while $f_{\text{OL}}$ and $f_{\text{OG}}$ are the two frequency limits, beyond which the overloading and excess generation begin in MG, respectively. Also, assume that parameters $f_{\text{OL}}$ and $f_{\text{OG}}$ are the MG's minimum and maximum allowed frequency to operate within the acceptable limit, while $f_{\text{OL}}$ is the no-load frequency and $f_{\text{min}}$ is the frequency where the MG becomes unstable due to excessive loading. In such a condition, the MG's operating status will be:

- The MG is HMG when $f_{\text{OL}} < f_{\text{MG}} < f_{\text{OG}}$.
- FMG can be attained in two conditions: when $f_{\text{OL}} < f_{\text{MG}} < f_{\text{FL}}$ (increasing load demand) or $f_{\text{FL}} < f_{\text{MG}} < f_{\text{OG}}$ (decreasing load demand).
- PMG can be attained in two conditions: when $f_{\text{min}} < f_{\text{MG}} < f_{\text{OL}}$ (overloaded) or $f_{\text{LIM}} < f_{\text{MG}} < f_{\text{max}}$ (excessive generation).

3 | PROPOSED STRUCTURE AND CONTROL TECHNIQUE FOR THE CONVERTERS

The proposed structure and control block diagram of the back-to-back converter topology are shown in Figure 2. In this scheme, the MSC and LSC enable bidirectional power flow between their dc link and respectively the MG and interconnecting line. Under the proposed approach, the MSC aims to regulate the dc-link voltage only; however, the operating mode of the LSC depends on the frequency of the MG to which it is connected. The control mechanisms of MSC and LSC are discussed in detail below.

The MSC is assumed to be a single-phase 3-leg VSC using IGBTs or MOSFETs. On the other hand, the LSC is assumed to be a single-phase H-bridge VSC. Each VSC is connected to its common point of coupling through an LCL filter (i.e. a three-phase LCL for the MSC and a single-phase Inductor-Capacitor-Inductor (LCL) for the LSC) [13,23]. The MSC and LSC structures are shown schematically in Figure 2.
It is to be noted that any other three-phase and single-phase topologies of VSCs can also be used instead of the topologies considered in this study for MSC and LSC, respectively.

3.1 | MSC control

The MSC's primary function is to maintain the dc-link voltage of $V_{dc}$ at the desired constant level of $V_{dc}^{ref}$. This is valid for any status of the MG (i.e. HMG, PMG, FMG). Through proper voltage regulation, the dc-link will exchange a suitable amount of power with the MG such that the voltage remains constant [24]. This is realised through a closed-loop control [24,25] (i.e. the outermost loop in the MSC part of Figure 2) to determine the reference for the active power ($P_{ref}$) that the MSC should draw from or inject to the MG to avoid a deviation in $V_{dc}$. The MSC is not expected to exchange any reactive power with the MG; thus, the reference of its output reactive power ($Q_{ref}$) is assumed to be zero. These quantities are then used to determine the three-phase reference voltage ($v_{ref}^{abc}$) across capacitor filter of $C_f$ at the output of the MSC [25]. The inner control loop in the MSC part of Figure 2 is the MSC’s switching control and modulation block. In this work, the linear quadratic regulator, implemented using a hysteresis controller, has been used to track the sinusoidal reference voltage, as discussed in [23]. However, any other voltage tracking and modulation technique can also be employed.

3.2 | LSC control

Two modes of operation are proposed for the LSCs in this study that depend on the status of the MG. It is suggested that to form a CMG, the LSC of all HMGs should operate under droop control, whereas the LSC of the FMGs and PMGs will operate in constant power (PQ) control mode (see the flowchart of Figure 3). The LSC connected to an HMG enables power exchange between the HMGs within a CMG, whereas it will draw a suitable amount of power from the interconnecting lines or inject them to alleviate the overloading or excess generation problems respectively when an MG becomes PMG.

For the above aim, the MGs' frequency should be monitored continuously. If the MG is overloaded, then a control system determines the level of power that should be imported from the interconnecting link to return the MG’s frequency to the acceptable range. This is also valid when the MG experiences excessive generation and its frequency rises beyond the acceptable range. Thus, when an MG becomes a PMG, its LSC will start operating in the constant PQ mode (see the flowchart of Figure 3). The reference of the active power ($P_{ref}$) is determined by a frequency deviation-based control system, while the reference of the reactive power ($Q_{ref}$) is again assumed to be zero. Once the overloading or overgeneration is alleviated, another frequency deviation-based control system will determine the new status of the system as a normal operation. In such a condition, the LSC of that MG should change from the constant PQ mode to the droop control mode, as shown in the flowchart of Figure 3.

Under the normal operation of the interconnected MGs (i.e. when all MGs are HMGs), the LSCs of all MGs operate under the droop control mode. The deployed droop control is in the form of voltage-angle droop. The LSC’s control mode change from droop to PQ and vice versa is achieved through a mode transition controller, which continuously monitors the MG’s frequency. Depending on the status of MG, the mode transition controller selects the voltage reference determined by the droop or PQ controller, as seen from Figure 2. The proposed droop control and the controller that enables the mode transition are discussed below.

FIGURE 2  MSC and LSC connection topology along with closed-loop control systems. LSC, line-side converter; MSC, microgrid-side converter.
3.2.1 | Modified droop control for HMG

Under the normal operation of the interconnected MGs (i.e. when all MGs are HMGs), the LSCs of all MGs operate under the voltage-frequency droop control mode (in contrary with the voltage-frequency droop that has been employed for the Distributed Energy Resources (DERs) within the MGs). By employing the angle droop instead of frequency droop, the frequency in the interconnecting lines is fixed at the desired frequency (e.g. 50 Hz). The angle and voltage droop equations for the $k$th MG can be written as [11,26]

$$\delta_k = \delta_o - n_{MG-k}P^g_k$$

(1a)

$$V_k = V_{max} - n_{MG-k}Q^g_k$$

(1b)

where $n_{MG-k}$ and $n_{MG-k}$ are the droop coefficients of the $k$th MG, and derived from

$$m_{MG-k} = (\delta_{max} - \delta_{min})/P^g_{max}$$

(2a)

$$n_{MG-k} = (V_{max} - V_{min})/2Q^g_{max}$$

(2b)

in which $P^g_{max}$ and $Q^g_{max}$ are the maximum active and reactive powers injected/absorbed by each MG. All MGs have similar $\Delta \delta = \delta_{max} - \delta_{min}$ and $\Delta V = V_{max} - V_{min}$. It is to be noted that the PQ to droop mode transition cannot be realised under the frequency droop as the voltages at the output of the LSC of all HMGs are at the same frequency; thus, synchronisation is not possible then. The proposed decentralised control mechanism would only work under angle-voltage droop control. However, the conventional angle-voltage droop cannot ensure the desired power sharing among the HMGs unless a modified angle droop [26,27] mechanism is implemented using the virtual impedance method. In order to implement the modified angle droop, (1) needs to be converted into the $a\beta$ coordinates and the voltage across the virtual impedance needs to be subtracted. Hence, the reference angle and voltage equation with the modified droop method can be rewritten in $a\beta$ coordinates as

$$V_{a-k}^{ref} = V_k \cos \delta_k + X^g_k I^g_k \sin \theta^g_k$$

(3a)

$$V_{b-k}^{ref} = V_k \sin \delta_k - X^g_k I^g_k \cos \theta^g_k$$

(3b)

where $X^g_k = \omega_{ref}^2 L^g_k$ and $I^g_k = \theta^g_k - \theta^g_{ref}$ are the virtual impedance and current of the coupling inductance, respectively. The reference voltage and phase angle for the LSC of MG-$k$ operating under the modified droop is then calculated as

$$V_{dr}^{ref} = \sqrt{V_{a-k}^{ref2} + V_{b-k}^{ref2}}$$

(4a)

$$\delta^k_{dr} = \tan^{-1} \left(\frac{V_{b-k}^{ref}}{V_{a-k}^{ref}}\right)$$

(4b)

From (4), the instantaneous voltage reference across the capacitor of $C_r$ of the LSC in MG-$k$ can be determined as

$$V_{a-k}^{ref} = V_{dr}^{ref} \sin \left(\omega_{ref}t + \delta^k_{dr}\right)$$

(5a)

$$V_{b-k}^{ref} = V_{dr}^{ref} \sin \left(\omega_{ref}t + \delta^k_{dr} + \pi\right)$$

(5b)

where $\omega_{ref}$ is based on the desired frequency in the single-phase ac line (e.g. 50 Hz). The virtual impedances to share...
power between MG-\(i\) and \(j\) can be calculated based on their droop coefficients as [26]

\[
m_{MG-i} = \frac{L_i + L_j}{L_i + L_j}
\]

(6)

The block diagram of the modified angle-voltage droop is shown in Figure 4. It may be noted here that the amount of power shared by each HMG will be determined by the central controller of that particular MG. Thus, the droop coefficient of \(m_{MG}\) will be modified based on (6) to achieve the desired power sharing.

4 | Frequency control for PMG

The proposed frequency control block is employed when an MG becomes a PMG. If the PMG is overloaded, then a control system termed as an overload frequency controller (OLFC) will determine the level of the power that should be imported from the neighbouring MGs to retain the MG frequency within the acceptable limit. Similarly, during overgeneration, the overgeneration frequency controller (OGFC) will get activated to determine the required power to export to the neighbouring MGs. Thus, when an MG becomes a PMG, its LSC will start operating in the constant PQ mode. An arrangement for such a control mechanism is shown in Figure 5 along with its control activation logic. The reference of the active power \(P_{ref}\) is determined by a frequency deviation-based control system, while the reference of the reactive power \(Q_{ref}\) is assumed to be zero. Once the overloading or overgeneration is alleviated, another frequency deviation-based control system will determine the new status of the system as the normal operation. In such a condition, the LSC of that MG should change from the constant PQ mode to the droop control mode.

The frequency controller determines the desired power reference through two different proportional-integral (PI) controllers, along with the necessary control logic and circuitry. Then, the desired power reference is selected through a \(4 \times 1\) multiplexer that selects the proper power reference during an overload or overgeneration situation respectively by activating the OLFC or OGFC.

In order to coordinate between the droop control mode (for HMG) and constant PQ control mode (for PMG and FMG), a proper reference selection logic is needed to switch between the modes smoothly and without causing unwanted transients, oscillations and instability. Such an arrangement to switch between modes of converter's operation is shown in Figure 6. The reference selector will select the three-phase reference voltages either from the droop control block or PQ controller block through \(2 \times 1\) multiplexer and pass it to the voltage tracking block. When the references are selected from the droop block, the PI controllers of the PQ block should be also reset to avoid integrator drift and unwanted overshoot upon activation. The switcher from droop to constant PQ mode is straightforward as only the reset signals need to be withdrawn. This also represents the scenario when an HMG becomes FMG or PMG. However, an additional line angle detection logic is required when a PMG/FMG becomes HMG. A PMG or FMG cannot be allowed to switch back to droop mode unless all remaining MGs are HMGs and operating in the same phase angle, \(\delta_0\) where \(\delta_0\) is the line voltage phase angle when there is zero or no power sharing.
among the MGs through the interconnecting lines. A line angle detection mechanism, consisting of a fast Fourier transform block and a window detector, is needed for this purpose to detect if all MGs are HMGs (Figure 6).

![Diagram of proposed mode transition and reference selection control block diagram](image)

**Figure 6** Proposed mode transition and reference selection control block diagram

| Parameter | Single-phase link | Three-phase link |
|-----------|-------------------|-----------------|
| No. of switching devices | 4 | 6 |
| No. of LCL filters | 1 | 3 |
| No. of current sensors | 2 | 6 |
| No. of voltage sensors | 2 | 6 |
| Number of single-phase lines | 1 | 3 |

**Table 1** Comparison of employing a single-phase ac link instead of a conventional three-phase ac link.

| Time instant | Study case 1 | Study case 2 |
|--------------|--------------|--------------|
| MG status    | MG-1 MG-2 MG-3 | MG status    | MG-1 MG-2 MG-3 | Action taken | Action taken |
| $t_1$ | OL HMG HMG | Normal operation for MG-2 and 3, while MG-1 is overloaded. | OG HMG HMG | Normal operation for MG-2 and 3, while MG-1 is overgenerating |
| $t_2$ | PMG HMG HMG | MG-1 is overloaded, while MG-2 and 3 are supporting it by supplying the overload power. | PMG HMG HMG | MG-1 is overgenerating, while MG-2 and 3 are supporting it by absorbing the excess power |
| $t_3$ | HMG HMG HMG | Overloading of MG-1 is over and all MGs become HMG. | HMG HMG HMG | Overgeneration of MG-1 is over and all MGs become HMG |

Abbreviations: MG, microgrid; HMG, healthy microgrid; PMG, problem microgrid.
to avoid saturation. Second, \( L_g \) cannot be made very small as the switching harmonics may not get filtered out and cause harmonic distortion in the voltage waveform. At the same time, in this study, the employed modified angle droop with virtual impedance is used to ensure proper power sharing among the HMGs. To implement such a droop control scheme, \( L_g \) needs to be large enough to decouple the active and reactive power sharing.

Considering all above points, the single-phase ac link is a better suit for this application because of reduced cost and less design complexities.

### 6 PERFORMANCE EVALUATION

To evaluate the dynamic performance of the proposed control, let us consider the system of Figure 1(a) with three MGs that have formed a CMG through the proposed single-phase interconnecting link and back-to-back converters. Each MG is operating under a voltage and frequency droop, as discussed in Appendix A, while the technical parameters of the network under consideration and the control are provided in Appendix B. The performance of such a system has been evaluated under various conditions, i.e. the normal, overloaded and over-generating, in two different case studies. Table 2 lists the events and scenarios applied to the MGs in each study case, during intervals \( t_1 \) to \( t_3 \), and the corresponding actions. The results of the study are presented in Figures 7 and 8. The results show the frequency of each MG and the injected/absorbed power from/to one MG to the interlinking lines (measured at the output of their corresponding LSCs). These figures also illustrate the dc-link voltage within the back-to-back converter, as well as the reference power and the voltage angle at the output of the LSCs. The transition of the control of the LSCs from droop to constant PQ mode and vice versa is also shown.

### 6.1 Case 1 (overloaded PMG)

This study case assumes that MG-1 has become provisionally overloaded; thus, the other two HMGs (i.e. MG-2 and 3) successfully support MG-1 by injecting the required power demand under the proposed power exchange and control strategy.

Initially, all MGs are assumed to be HMGs and operating at the steady-state condition and under the droop control. At, \( t = t_1 \), MG-1 becomes overloaded by 18% (see Figure 7(a)); hence, its frequency decreases from 49.85 to 49.38 Hz (see Figure 7(c)). As the frequency has fallen beyond the acceptable limit of 49.5 Hz, MG-1 becomes a PMG. Thus, the LSC controller of MG-1 senses this situation and switches its mode of operation from droop to constant PQ control after a certain time delay (i.e. 0.7 s). With this change, the frequency controller gets activated and determines the amount of power

![Figure 1](https://example.com/figure1.png)

![Figure 2](https://example.com/figure2.png)

**FIGURE 7** Simulation results of study case 1
that needs to be transferred to MG-1 to retain its frequency back to the acceptable limit. Thus, at $t = t_2$, MG-2 and MG-3 start injecting the required power of 0.174 and 0.086 pu as demanded by MG-1, respectively. The power sharing between MG-2 and MG-3 is determined by the assumed (desired) droop ratio (i.e. 1:2 in this case); thus, the power delivered by MG-2 is twice of that of MG-3, as seen from Figure 7(b). The required power demand of MG-1 is 0.237 pu and the rest of the power is to overcome the line losses. This continues until $t = t_3$ in which the overloading situation is alleviated. At $t = t_3$ the overload is removed, and as soon as this occurs, the frequency of MG-1 increases to 49.86 Hz (i.e. above the level of minimum acceptable limit). Therefore, MG-1 goes back to its nominal operating condition and becomes an HMG. Hence, MG-2 and MG-3 cease to transfer power to MG-1. After the MG-1 settles back as HMG and steady-state condition is reached, the LSC controller of MG-1 switches its mode of operation from constant PQ to droop control.

### 6.2 Case 2 (excessively generating PMG)

This study case assumes that MG-1 experiences an excess power generation from its renewable-based DGs; thus, the other two HMGs (i.e. MG-2 and 3) successfully support MG-1 by absorbing the required portion of this excess power under the proposed power exchange and control strategy.

Initially, all MGs are assumed to be HMGs and operating at the steady-state condition and under the droop control. At $t = t_1$, MG-1 experiences an excessive power generation by 17% (see Figure 8(a)), and its frequency increases from 50.03 to 50.36 Hz (see Figure 8(c)). As the frequency has increased beyond the acceptable limit of 50.2 Hz, MG-1 becomes a PMG. Thus, the LSC controller of MG-1 senses the situation and switches its mode of operation from droop to constant PQ control after a certain time delay (i.e. 0.7 s). With this change, the frequency controller gets activated and determines the amount of power that needs to be exported from MG-1 to retain its frequency back to the acceptable limit. Thus at $t = t_2$, MG-2 and 3 start absorbing the required power of 0.104 and 0.051 pu, respectively. The power sharing between MG-2 and 3 is again maintained as 1:2, as seen from Figure 8(b). The power delivered by MG-1 is 0.16 pu. This continues until $t = t_3$ in which the situation of excessive generation in MG-1 is alleviated. As soon as this occurs, the frequency of MG-1 decreases to 50.02 Hz (i.e. below the level of maximum acceptable limit). Therefore, MG-1 goes back to its nominal operating condition and becomes an HMG. Hence, MG-2 and MG-3 cease to absorb power from MG-1. After MG-1 settles back as HMG and steady-state condition is attained, the LSC controller of MG-1 switches its mode of operation from constant PQ to droop control.

### 6.3 Case 3 (two PMGs: one overloaded and one excessively generating)

Let us assume that the system is at a steady-state condition initially, and all MGs are healthy and the LSCs are operating under droop. At $t = t_1$, MG-3 experiences overgeneration by
8% after an internal demand decrease (see Figure 9(a)), and hence, its frequency rises to 50.28 Hz (higher than the maximum frequency limit of 50.2 Hz). Thus, after a predefined delay of 0.6 s, MG-3 changes its operation mode from droop to constant PQ control, and at \( t = t_5 \), MG-1 and 2 start to absorb the excess power from MG-3 so that its frequency is retained back to the acceptable limit (see Figure 9). Note that, the power delivered by MG-2 \( (P_{g2} = -0.0474 \text{ pu}) \) is twice of that of MG-1 \( (P_{g1} = -0.024 \text{ pu}) \). This is determined by the employed 1:2 droop ratios between these MGs (see Figure 9(b)). At \( t = t_5 \), MG-1 becomes overloaded by 10% and its frequency falls to 49.4 Hz. As such, it turns into an FMG and later a PMG after 0.6 s of delay at \( t = t_6 \). In such a condition, MG-1 changes its operation mode from droop control to constant PQ control with zero power sharing (i.e. the floating mode) as it is not participating in absorbing any excess power from MG-3. During this interval, MG-2 absorbs all the excess power of MG-3 alone. At \( t = t_5 \), MG-1 starts to receive power from both overgenerating PMG of MG-3 and HMG of MG-2. First, MG-1 absorbs the total overgenerating power \( (P_{g3} = 0.075 \text{ pu}) \) of MG-3 and the rest of the overload demand is supplied by MG-2 \( (P_{g2} = 0.025 \text{ pu}) \) to retain MG-1’s frequency back to the minimum limit of 49.5 Hz. At \( t = t_6 \), MG-1’s overloading is eased following the reduction in its internal demand by 10%. Thus, MG-1 becomes an HMG. However, it cannot be allowed to switch back to droop mode as it cannot be synchronised with the interconnecting link. Therefore, it continues its operation under the constant PQ mode but with zero output power reference (as an FMG). In this condition, the excess power of MG-3 is consumed by MG-2 only. Finally, at \( t = t_6 \), the overgeneration of MG-3 is over and all MGs become HMGs, but both MG-1 and MG-3 will continue to operate as FMG until the droop angle of the interconnecting lines returns back to \( \delta_c \). Once the desired value of \( \delta_c \) is attained, indicating that there is no power exchange taking place in the link (i.e. all MGs are HMGs), and after a preset delay of 2 s (determined by the mode transition controller), both MG-1 and 3 change their operation mode back to the droop mode. All MGs resume operating under their normal condition with no power flow in the power exchange link. Table 3 summarises the events applied to the MGs and the corresponding actions taken according to the proposed control mechanism for study case 3.

7 | SENSITIVITY ANALYSIS

Another study has been carried out to evaluate the sensitivity of the proposed power exchange and the control strategy against the design and operational parameters. This study aims at determining how the tie-line impedance (the distance of the MGs from each other) and the amount of power injected or demanded by a PMG affects the parameters such...
as power exchange link’s line loss, the amount of delivered power from HMGs to PMG, the HMG’s frequency and the LSC’s voltage and angle droop. The study is carried out for both overloading (case 1) and overgeneration (case 2) scenarios of Section 5. This study is repeated for the CMGs of study case 1 and 2, assuming that a three-phase interconnecting link was deployed to deduce a comparison between the sensitivity of the single and three-phase links to the variations of the same parameter. The results are provided in Figures 10–14 and tabulated in Table C1 to C3 of Appendix C for a more accurate presentation.

The study shows that the sharing of power among the HMGs according to their droop ratios is slightly affected as the impedance of the tie line (i.e. the distance among the MGs). Conventional angle droop technique is highly sensitive to line impedances and it requires that the line reactance should be much larger than its resistance, which is not always possible for the scenarios taken into consideration in this study. Moreover, larger droop coefficients tend to make the system more unstable. So to ensure enough stability margins droop coefficients are chosen to be small enough, but such a design fails to share desired power among the MGs according to their droop coefficients. Hence, the modified angle droop method used in this study is a possible way to ensure the desired power sharing among the HMGs. One of the primary objectives of this sensitivity analysis is to observe the ability to share power among the HMGs operating under the modified angle droop while line impedances are varied, and the line resistances are larger compared to their inductances.

### 7.1 Line impedance variation

The variation of HMG’s shared power through the ac link, droop angles, voltages, line loss and percentage of error in power sharing as the impedance varies are shown in Figure 10(a)–(b). These graphs are plotted considering the situation as described in the study cases 1 and 2 (i.e. when one PMG is supported by two HMGs with a power-sharing ratio of 2:1) for both single- and three-phase link. The line impedance used in the simulation for case studies is used as a reference and all parameters are normalised based on this value. The PMG power demand is assumed to be 5 kW (in both overgeneration and overloading scenario). It can be observed from Figure 10(a)–(d) that, as the line impedance is increased, the loss and power delivered by the MGs increase, whereas the line's droop angle and voltages start to drop, as per their droop coefficients, to accommodate the excess power required due to the line loss. The frequency of each MG also drops as the delivered power by them increases. These variations are almost linear and as expected. Figure 10(e) and (f) shows the line loss and the percentage of error in power sharing according to their droop ratio, as the line impedance increases. It is interesting to note that the loss in the single-phase link is higher compared to the three-phase link, whereas the error in power sharing is higher in the three-phase link. As the current in a three-phase link is three times smaller than that of a single-phase link, the line loss is less. On the other hand, single-phase link offers better accuracy in power sharing among the MGs based on their droop coefficient. The line loss and percentage of error are also shown with respect to HMG’s total power variation due to line impedance variation.

Figures 11 and 12 show the surface plot of line loss, droop angle, voltage and error percentage in power sharing as the power delivered by two HMGs is varied due to an increase in the line impedance for overload and overgeneration scenarios, respectively. The graphs of droop angles of each HMG follow a similar pattern, whereas the droop voltages are not similar. As the impedance of the tie lines is increased, the property of sharing of desired power, as per the droop coefficients, starts to deviate slightly and
produces an error. This is due to the fact that, as the impedances of the lines become larger, the property of power sharing, as the reciprocal of the droop coefficients, does not remain valid any longer. As can be seen from Figure 11(d), the variation of impedance causes an error of −8 to +4% during the considered overloading case. During overgeneration, the error ranges from −8 to +2%, as can be seen from Figure 12(d). In both cases, the error stays in an acceptable range because of employing the modified angle droop, which is an effective way to ensure accurate power sharing among the MGs.

7.2 PMG power variation

The second sensitivity analysis was carried out by varying the PMG's power demand in both overloading and overgeneration cases. Figure 13 shows the sensitivity analysis for CMG during the overloading scenario as the power absorbed by the PMG varies from 2 to 10 kW. The delivered HMG power, line loss, the HMG's droop angle, voltage, and error percentage in power sharing are plotted as a function of the PMG's power demand. The plots are normalised based on a value of 6 kW. Figure 14 shows a similar sensitivity analysis during overgeneration.
It can be seen from Figures 13 and 14 that the sharing of power between the two HMGs remains constant irrespective of the PMG’s power demand. Hence, negligible error in power sharing according to their droop ratio is observed in this analysis. In other words, the proposed power-sharing approach using a modified angle droop method is insensitive to the PMG’s power demand.
8 | STABILITY ANALYSIS

Another study has been carried out to evaluate the stability of the proposed power exchange strategy. The stability analysis is conducted by varying several design parameters such as the active and reactive power droop coefficients, interconnecting line's impedance and the PMG's power demand in both overloading and overgeneration cases. The obtained eigenvalue plots for the stability analysis are shown in Figure 15.

The studies show that, among all these parameters, the active power droop coefficient, $m_{MG}$, has the most dominating effect and can lead the CMG towards instability, whereas the other parameters affect the CMG’s dynamics and response but have less impact on the system’s stability.

8.1 | Variation of droop coefficients

First, the active power droop coefficient of $m_{MG}$ is varied from its nominal value of 0.002 rad/kW while the reactive power droop coefficient of $n_{MG}$ is held constant. The coefficient $m_{MG}$ and $n_{MG}$ are defined in (2a) and (2b), respectively. It can be observed from Figure 15(a) that the critical value for $m_{MG}$ is obtained as $m_{crit} = 0.125$ rad/kW. Any further increase in the value of $m_{MG}$ will make the CMG unstable. On the other hand, the variation of $n_{MG}$ does not have any significant effect on the stability of the CMG. This is because the reactive power flow through the CMG link is very small, and hence the variation of $n_{MG}$ does not have a pronounced effect on the system stability, as seen from Figure 15(b).

8.2 | Variation of PMG power

The dynamic response of the CMG is also affected by the amount of power absorbed (overload) from or injected (overgeneration) to the CMG by the PMG. This is shown in Figure 15(c) and 15(d). In both cases, the power is varied from 2 to 10 kW. The non-dominant eigenvalues are almost identical for both cases but the location and behaviour of the dominant eigenvalues differ slightly in case of overload and overgeneration.

8.3 | Variation of line impedance

The impedance of the line was varied to see the effect on stability. The line inductance of $L_{line}$ is increased from 0.1 to 1.2 mH, while the resistance of $R_{line}$ is held constant. The same was repeated by increasing $R_{line}$ from 0.1 to 1.2 ohm, while $L_{line}$ is held constant. The resultant eigenvalues are shown in Figure 15(e) and 15(f). It can be observed that an increase in the inductance decreases the system damping, while an increase in resistance introduces more damping in the system.

9 | DISCUSSION

The main objective of this research is to investigate the efficacy and feasibility of employing a single-phase ac power exchange link for the coupling of multiple MGs to exchange power among them during any emergency like power
shortfall, overloading or overgeneration. A suitable power exchange mechanism is developed along with the proper control and coordination of the converters to successfully and effectively share power among the interconnected MGs to alleviate any emergency situation to ensure system reliability, resiliency, and stability to some extent. The proposed mechanism is verified through three extensive simulation-based case studies that show the system can alleviate both

**FIGURE 15** CMG stability analysis: eigenvalue trajectory for variation of (a) mMG, (b) nMG, (c) POL, (d) POG, (e) Lline, (f) Rline. CMG, coupled microgrid.
overloading and overgeneration scenario simultaneously in a totally decentralised manner and without any data communication link. The key motivation of using a single-phase ac link over a three-phase link to couple MGs is to reduce cost as the number of equipment and interconnecting conductors will be less. However, this is true in the case of autonomous MGs located in close proximity. If the distance among the MGs is large, then the advantages of the proposed single-phase links over three-phase links may not remain valid anymore. One other possibility is to use a dc link to couple MGs but, the protection equipment for dc systems is expensive compared to ac systems. Moreover, dc systems would be proven to be cost-effective at the same voltage level if the distance among the MGs is high.

The sensitivity analysis of the proposed single-phase link shows that the loss in the three-phase link is lower than in the single-phase link as the current in three-phase star-connected system will be three times less compared to the single-phase system for the same phase to neutral voltage. However, this can be addressed by the proper selection and design of cables. The sensitivity studies also show that the single-phase ac link is more efficient in sharing power according to the droop coefficients in comparison to the three-phase link.

Finally, the stability studies show that the stability of the CMG is mostly affected and dominated by the active power droop coefficient, while the reactive power droop coefficient does not affect the CMG stability significantly. The line impedance moderately affects the CMG dynamics but did not show a prominent impact to cause instability. The power consumed and injected by a PMG also affects the system dynamics. A larger power provides more damping and makes the system's response sluggish, whereas a smaller power reduces the system damping and system's response becomes oscillatory.

10 | CONCLUSION

This article has discussed the mechanism of interconnecting neighbouring MGs to each other to exchange power during power deficiency or surplus, realised through a single-phase ac link and back-to-back VSC. A decentralised frequency deviation-based control technique has been proposed to realise proper power exchange from HMGs to PMGs. The proposed power exchange mechanism includes an approach to realise the desired power-sharing ratio among multiple HMGs and various control techniques for the detection of the MG status, determining the power exchange level and transition between the various modes of operation based on local measurements only. The numerical simulation studies in PSIM® have
validated the effective and successful operation of such a system in alleviating the unacceptable frequency deviation in the MGs, following a power shortfall or excess. The proposed mechanism provides a solution that can effectively replace load shedding or curtailment of renewable sources under such conditions. The sensitivity analysis of such a CMG demonstrates an almost linear variation of the different parameters of the control mechanism with respect to the design and operational factors, and thus offers a reasonably robust performance against variations in those parameters. The stability analysis shows that the system’s stability is dominated by the considered active power droop coefficients of the coupling converters, used to connect the MGs to the ac power exchange link while the other factors do not affect the CMG’s stability significantly. The future work of this study may include implementation and validation of the proposal using a hardware-in-the-loop study testbed.

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APPENDIX

A. Droop control within MGs

This section describes the assumed operational principle for the considered MGs in this study. Each MG is assumed to be consisting of several droop controlled DERs in which the voltage and frequency at their output is defined by

\[
f_{MG} = f_{\text{max}} - m_i P_i \quad (A1)
\]
\[
V = V_{\text{max}} - n_i Q_i \quad (A2)
\]

where \(m_i\) and \(n_i\) are droop coefficients of a DER, and derived from

\[
m_i = (f_{\text{max}} - f_{\text{min}}) / P_{\text{max}} \quad (A3)
\]
\[
n_i = (V_{\text{max}} - V_{\text{min}}) / 2Q_{\text{max}} \quad (A4)
\]

| TABLE B1 | Technical data of network under consideration |
|-----------|-------------------------------------------------|
| Network   | \(V_{\text{nom}} = 415 \text{ V}, f_{\text{nom}} = 50 \text{ Hz}, f_{\text{min}} = 49.5 \text{ Hz}, f_{\text{max}} = 50.2 \text{ Hz}, P_{\text{max}} = 100 \text{ kW}, V_{dc} = 1.5 \text{kV}, Z_{dc} = 0.1 + j0.5 \Omega, Z_{line} = 0.1 + j0.08 \Omega \) |
| DER droop | \(m = 0.01 \text{ Hz/kW}, n = 0.1 \text{ V/kVAR} \) |
| Angle droop| \(m_d = 0.002 \text{ rad/kW}, n_d = 0.004 \text{ V/kVAR} \) |
| VSC and filters | \(R_1 = 0.12 \Omega, L_1 = 2 \text{mH}, R_{\text{MSC}} = 0.04 \Omega, L_{\text{MSC}} = 1.36 \text{mH}, R_{\text{LSC}} = 0.12 \Omega, L_{\text{LSC}} = 10 \text{mH}, C_1 = 25 \mu \text{F}, C_{dc} = 4700 \mu \text{F} \) |
| Linear quadratic regulator gains | \(k_1 = 58.63, k_2 = 97.18, k_3 = 1.2, \omega_c = 6283.2 \text{ rad/s} \) |
| PI – PQ controller (MSC) | Proportional Gain, \(K_p = 0.628\), Time Constant, \(T_c = 0.034 \text{ s}, f_{\text{OL}} = 73.5 \text{ Hz} \) |
| PI – PQ controller (LSC) | Proportional gain, \(K_p = 0.628\), time constant, \(T_c = 0.0834 \text{ s}, f_{\text{OL}} = 10 \text{ Hz} \) |
| Frequency controller | \(K_{\text{cF}} = 15 \text{ k}, T_{\text{cF}} = 0.025 \text{ s}, \omega_{\text{cF}} = 314 \text{ rad/s}, K_{\text{cG}} = 20 \text{ k}, T_{\text{cG}} = 0.05 \text{ s}, \omega_{\text{cG}} = 37.7 \text{ krad/s} \) |
| DC link voltage controller | \(K_{\text{cV}} = 222, \omega_c = 2.2 \text{ rad/s}, \omega_{\text{cV}} = 1000 \text{ rad/s}, \tau_{\text{dc}} = 392.2 \text{ms}, P_{\text{dc}} = 100 \text{kW}, V_d = 380 \text{ V} \) |

| TABLE C1 | Sensitivity analysis results during overgeneration |
|-----------|--------------------------------------------------|
| MG coupling link types | \(1\)-ph | \(3\)-ph | \(1\)-ph | \(3\)-ph | \(1\)-ph | \(3\)-ph | \(1\)-ph | \(3\)-ph |
| PMG Power (kW) | \(\delta_1\) (deg) | \(\delta_2\) (deg) | \(\delta_1\) (deg) | \(\delta_2\) (deg) | \(P_1\) (kW) | \(P_2\) (kW) | \(P_1\) (kW) | \(P_2\) (kW) | Line loss (kW) | Line loss (kW) | % error | % error |
| 2 | 64.79 | 64.81 | 61.67 | 61.66 | 0.655 | 1.337 | 0.671 | 1.327 | 0.008 | 0.002 | 2.06 | 1.12 |
| 4 | 69.56 | 69.61 | 63.21 | 63.19 | 1.345 | 2.623 | 1.327 | 2.659 | 0.03 | 0.014 | 2.49 | -0.19 |
| 6 | 74.63 | 74.71 | 64.77 | 64.75 | 1.979 | 3.946 | 1.990 | 3.977 | 0.07 | 0.033 | 0.30 | 0.07 |
| 8 | 80.26 | 80.37 | 66.37 | 66.34 | 2.612 | 5.252 | 2.663 | 5.283 | 0.14 | 0.033 | -0.54 | 0.81 |
| 10 | 86.99 | 87.15 | 67.95 | 67.91 | 3.216 | 6.544 | 3.322 | 6.588 | 0.24 | 0.054 | -1.74 | 0.84 |

Abbreviation: MG, microgrid.

| TABLE C2 | Sensitivity analysis results during overloading |
|-----------|-------------------------------------------------|
| MG coupling link types | \(1\)-ph | \(3\)-ph | \(1\)-ph | \(3\)-ph | \(1\)-ph | \(3\)-ph | \(1\)-ph | \(3\)-ph |
| PMG power (kW) | \(\delta_1\) (deg) | \(\delta_2\) (deg) | \(\delta_1\) (deg) | \(\delta_2\) (deg) | \(P_1\) (kW) | \(P_2\) (kW) | \(P_1\) (kW) | \(P_2\) (kW) | Line loss (kW) | Line loss (kW) | % error | % error |
| 2 | 55.40 | 55.37 | 58.44 | 58.45 | 0.665 | 1.343 | 0.674 | 1.332 | 0.008 | 0.006 | -0.97 | 1.20 |
| 4 | 50.51 | 50.47 | 56.84 | 56.85 | 1.347 | 2.687 | 1.341 | 2.682 | 0.034 | 0.023 | 0.26 | -0.11 |
| 6 | 45.34 | 45.26 | 55.23 | 55.26 | 2.032 | 4.048 | 2.010 | 4.026 | 0.080 | 0.036 | 0.39 | -0.15 |
| 8 | 39.30 | 39.20 | 53.62 | 53.65 | 2.724 | 5.429 | 2.696 | 5.369 | 0.153 | 0.066 | 0.35 | 0.44 |
| 10 | 32.00 | 31.85 | 51.95 | 51.98 | 3.443 | 6.821 | 3.381 | 6.717 | 0.264 | 0.098 | -0.94 | 0.66 |

Abbreviation: MG, microgrid.
where subscript $\text{max}$ and $\text{min}$ represent the maximum and minimum allowable limits for frequency and voltage of the MGs, while $P_i$ and $Q_i$ are active and reactive powers injected by each DER to the MG. All DERs within an MG have similar $\Delta f = f_{\text{max}} - f_{\text{min}}$ and $\Delta V = V_{\text{max}} - V_{\text{min}}$; however, these quantities can be different in the neighbouring MGs, an issue which necessitates employing back-to-back VSC in the proposed concept. The structure and operation of the DERs are discussed in [23] and are not repeated here.

### B. Technical data

These technical data used for case studies in this paper are listed in Table B1.

### C. Sensitivity analysis tables

The sensitivity analysis results are tabulated in Table C1 to C3 for a more accurate presentation of the results plotted in Figures 10 to 14.

**Table C3** Sensitivity analysis results for line impedance variation

| line impedance (ohm) | 1-ph $\delta_1$ (deg) | 1-ph $\delta_2$ (deg) | 1-ph $P_1$ (kW) | 1-ph $P_2$ (kW) | 1-ph $\text{Line loss}$ (kW) | 3-ph $\%$ error | 3-ph $\%$ error |
|----------------------|------------------|------------------|----------------|----------------|----------------|----------------|----------------|
| 0.1                  | 48.09            | 56.0             | 1.688          | 3.366          | 0.054          | 0.296          | 0.239          |
| 0.3                  | 47.88            | 56.04            | 1.718          | 3.445          | 0.163          | 0.074          | 0.262          | 1.027          |
| 0.5                  | 47.64            | 56.02            | 1.751          | 3.530          | 0.281          | 0.118          | 0.799          | 2.081          |
| 0.7                  | 47.39            | 56.01            | 1.791          | 3.620          | 0.411          | 0.173          | 1.061          | 3.206          |
| 0.9                  | 47.09            | 55.98            | 1.838          | 3.720          | 0.558          | 0.229          | 1.197          | 4.588          |
| 1.1                  | 46.67            | 55.95            | 1.896          | 3.851          | 0.747          | 0.289          | 1.556          | 5.885          |
| 1.3                  | 45.91            | 55.92            | 1.960          | 3.997          | 0.960          | 0.338          | 2.015          | 7.349          |

Abbreviation: MG, microgrid.