A Fully Decentralized Approach for Mitigating Destructive Disturbances in Isolating Process of Remote Coupled Microgrids

Ehsan Pashajavid and Arindam Ghosh
Department of Electrical and Computer Engineering
Curtin University
Perth, Australia

***Abstract*—Coupling remote microgrids (MGs) is a promising technique to handle the overloading challenges in such systems. The criteria based on which the interconnection procedures should be performed have been investigated under decentralized strategies. However a~~A~~s soon as ~~the~~ power shortfall is removed, the coupled MGs (CMG) should be isolated to carry on their operation independently. Due to the non-zero power still flowing through the tie-line, however, considerable voltage spikes may be imposed on the interconnecting instantaneous static switch (ISS) during the isolation that may damage the device. This paper proposes a practical decentralized approach to efficiently alleviate the mentioned transients, facilitating a successful MG isolation procedure~~ of the MGs~~. Two auxiliary controllable loads (ACL) are to be considered at two sides of the ISS. As soon as the necessity of applying the isolation action is detected, the ISS controller commands the ACL on the supporting MG side to connect. A droop-based scheme is formulated to derive the load should be demanded by the ACL such that the power passing through the ISS drops to zero, preventing any spikes across it at the opening moment. Once the isolation action is accomplished, the controller commands the ACL to disconnect. The efficiency of the proposed algorithm is validated through various cases simulated using PSCAD/EMTDC.**

***Index Terms*-- Coupled Microgrids, Distributed generation, Droop control, Islanded Microgrids, Remote Area.**

I. INTRODUCTION

Isolation of rural and remote areas from main electricity systems is one of the main motivation behind utilizing distributed generators (DG) to supply their electric demands [1]. This type of electrification systems can be realized under an islanded microgrid (MG) framework [2]. Without getting any support from the main grid, the control of a remote MG is more complex than the grid-connected ones. In addition, remote areas usually suffer from poor and unreliable communication infrastructures. Thus, droop control schemes are often employed for regulating frequency and voltage of these MGs as well as proper load sharing among the utilized DGs since they show superior capabilities based on only the local measurements [3].

Remote MGs are prone to experience power deficiency challenges due to their limited power generation capacities [4]. A variety of techniques such as utilizing extra-sized diesel generators along with employing energy storage systems were suggested in the literature in order to provide frequency support for the overloaded MGs [5-6]. The controllability of islanded MGs was improved in [7] via applying energy storage devices controlled by a hybrid method. In order to maintain the supply-demand balance within an MG, a distributed cooperative control strategy was suggested in [8] based on which the utilized batteries were coordinated. The installation and operating costs of an energy storage system nevertheless are considerable.

The idea of coupling neighboring MGs is lately presented as an economically promising alternative since it imposes almost no capital investment on the owners [9-12]. In this concept, if an MG confronts a power deficiency, while there is surplus generation capacity in DGs of its neighboring MG, coupling these MGs to form a system of coupled MG (CMG) can alleviate the overloading problem. Considering a droop-based decentralized strategy, the required conditions and constraints to perform such interconnection procedures have been studied in [11]. The CMG can be formed by closing the instantaneous static switch (ISS) mounted on the tie-line between the neighboring MGs. Although the CMG forming issue has been investigated in the literature in detail, the realization of a proper decentralized mechanism for isolating the coupled MGs has been neglected. Once the power shortfall is removed, the MGs should isolate to carry on their normal operation independently. Due to the dissimilar configuration of the MGs, however, a non-zero power may still flow through the tie-line. In this case, inappropriate isolation of the MGs can impose considerable voltage spikes on the ISS that may damage the device.

This paper proposes a practical communication-free approach to facilitate a successful isolation procedure of the coupled MGs, efficiently mitigating the above mentioned destructive disturbances. The scheme is based on equalizing the load-to-capacity (L2C) ratios of the MGs such that the power flowing through the ISS decreases to zero. Once the necessity of applying an isolation action is detected, the ISS controller commands an auxiliary controllable load (ACL) on the supporting MG side to connect. The reference value of the load that should be demanded by the ACL is accurately derived based on only the local measurements. The validity of the proposed strategy is verified through the case studies performed on PSCAD/EMTDC and found to be very effective in achieving the desired performance.

This paper is organized as follows. An introduction to the raised issue is presented in Section I. Configuration of the system under study is described in Section II. The proposed strategy to address the problem is presented in Section III. Section IV appraises performance the proposed scheme based on the outcomes of the conducted simulations. The paper is concluded in Section V.

II. BASIC STRUCTURE OF THE CONSIDERED MGS

Consider the two neighboring remote MGs of Fig. 1 consisting of N_1 and N_2 droop-controlled DGs~~ respectively~~. Let us assume the MGs are of different capacities and none of them benefits from any communication infrastructure. In each MG, voltage magnitude and frequency at the output of each DG is regulated by droop control as [3]

$$f = f_{\max} - m_{DG} P_{DG} \quad , \quad V = V_{\max} - n_{DG} Q_{DG} \tag{1}$$

where m_{DG} and n_{DG} are respectively the P– f and Q–V droop gains, $f_{\max}$ and $V_{\max}$ are respectively the maximum of frequency and voltage magnitude in the MG, and P_{DG} and Q_{DG} are respectively the active and reactive powers injected by the DG. For each DG, m and n are derived from

$$m_{DG} = (f_{\max} - f_{\min}) \big/ P_{DG}^{cap} \quad , \quad n_{DG} = (V_{\max} - V_{\min}) \big/ Q_{DG}^{cap} \tag{2}$$

where superscript *cap* indicates power capacity of DGs and $f_{\min}$ and $V_{\min}$ are respectively the minimum of frequency and voltage magnitude in the MG. The load sharing between any two DGs e.g. i^{th} and j^{th}, is fulfilled according to their droop coefficients as follows

$$\frac{P_{DG\text{-}i}}{P_{DG\text{-}j}} = \frac{m_{DG\text{-}j}}{m_{DG\text{-}i}} \rightarrow \frac{P_{DG\text{-}i}}{P_{DG\text{-}j}} = \frac{P_{DG\text{-}i}^{cap}}{P_{DG\text{-}j}^{cap}} \tag{3}$$

The MGs can be interconnected by closing the ISS mounted on the tie-line, as can be seen from Fig. 1.a. The ISS controller manages the decentralized operation using only the local measurements. Excluding the ACLs, the Thevenin equivalent of the system seen from the two sides of the ISS is demonstrated in Fig. 1.b where Z_{MG} and V_{MG} indicate the equivalent impedance and voltage of an MG respectively while $Z_{Tie\text{-}line}$ is the impedance of the tie-line. The equivalent circuit is presented assuming the ISS is in the middle of the tie-line.

III. THE PROPOSED STRATEGY

Coupling of neighboring MGs can be a more economical alternative to traditional frequency support methods, particularly in remote areas rich in renewable resources. The idea is to interconnect two isolated MGs if one of them suffers from power deficiency while DGs of the other one have surplus generation capacity. Consider the system of two isolated MGs shown in Fig. 1.a. In this system, DGs of each MG are regulated by droop control with the same maximum frequency deviations. The interconnection can be done by closing the normally-open ISS sited on the tie-line. By forming a CMG system the total load will be shared by DGs of the both MGs. The criteria for the interconnection procedure are briefly presented in this section. Afterward, the concerns may be confronted during the isolation stage are described and then, properly addressed via the proposed decentralized strategy.

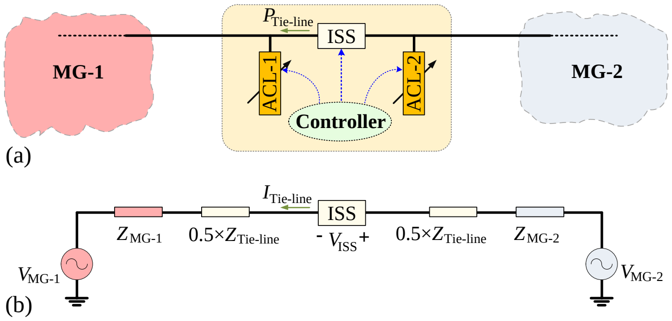


Fig. 1 (a) The network of two remote neighboring microgrids, (b) the Thevenin equivalent of the considered microgrids.

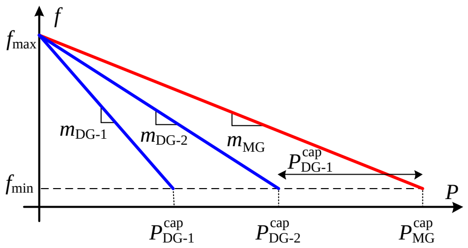


Fig. 2. Equivalent droop curve of an MG along with droop curves of its DGs.

A. Coupling algorithm [reference?]

Let us assume MG-1 experiences a power shortfall if its frequency, $f_{MG\text{-}1}$, drops below a threshold defined as

$$f_{MG\text{-}1} < f_{\min} + \alpha(f_{\max} - f_{\min}) \tag{4}$$

where $0<\alpha<1$. In this case, the controller commands the ISS to close subject to the availability of the required surplus power in MG-2. It can be shown that this constraint is satisfied if the frequency of MG-2, $f_{MG\text{-}2}$, meets the following criterion

$$f_{MG\text{-}2} > f_{\max} - m_{MG\text{-}1} \times \left[(1-\alpha_2) \times (P_{MG\text{-}1}^{cap} + P_{MG\text{-}1}^{cap}) - \frac{f_{\max} - f_{MG\text{-}1}}{m_{MG\text{-}1}} \right] \tag{5}$$

where $P_{MG\text{-}1}^{cap}$ and $P_{MG\text{-}2}^{cap}$ indicate total power capacity of all DGs of the MG-1 and MG-2 respectively and m_{MG} is the equivalent droop slope of all DGs of an MG explained as

$$m_{MG} = 1 \Big/ \sum_{i=1}^{N} \frac{1}{m_{DG\text{-}i}} \tag{6}$$

Fig. 2 shows the equivalent droop curve of an MG assuming the MG consists of only two DGs. This example demonstrates how the whole DGs can be aggregated in a single unit representing the droop behavior of the MG.

The controller activates the ISS if both (4) and (5) are satisfied. Then, the ISS closes when voltages at its two sides are synchronized.

B. *Problem statement*

By forming the CMG system, MG-2 supports MG-1 with a supporting power of $P_{\text{Tie-line}}$ that flows through the tie-line. Using (1), (2) and (4), it can be proved that MG-1 requires receiving the support from MG-2 as long as $P_{\text{Tie-line}}$ can be stated as

$$P_{\text{Tie-line}} > (1-\alpha)\times P^{\text{cap}}_{\text{MG-1}} - (f_{\max} - f_{\text{CMG}})/m_{\text{MG-1}} \tag{7}$$

However, if $P_{\text{Tie-line}}$ drops below the above limit, the interconnection is no longer required. In other words, the violation of (7) means the state of power deficiency in MG-1 is already removed and now, the MGs should be isolated.

Regarding the Thevenin equivalent of the CMG system shown in Fig. 1.b, the voltage across the ISS can be stated as

$$v_{\text{ISS}}(t) = L_{\text{Eq}}\frac{di_{\text{tie-line}}(t)}{dt} + R_{\text{Eq}}i_{\text{tie-line}}(t) + v_{\text{Eq-MGs}}(t) \tag{8}$$

where L_{Eq} and R_{Eq} are the equivalent inductance and the resistance of the system seen from the ISS respectively while $v_{\text{Eq-MGs}}$ indicates the resultant voltage of the sources. It is to be noted that although the violation of (7) indicates the necessity of an isolation action, a supporting power may still pass through the ISS. Due to the derivative term of (8), the ISS may experience the destructive transients whenever the isolation is executed by opening the switch while it is conducting a non-zero current. Thus, a proper mechanism should be developed to facilitate a successful isolation procedure such that neither the ISS nor the other components of the system are damaged.

C. *The proposed scheme*

By forming a CMG system, the total load of the system, $P_{\text{Load}} = P^{\text{Load}}_{\text{MG-1}} + P^{\text{Load}}_{\text{MG-2}}$, is shared by DGs of the MGs regarding the ratios stated in (3). Assuming

$$P^{\text{cap}}_{\text{MG-1}}/P^{\text{cap}}_{\text{MG-2}} = k \tag{9}$$

thus, the total power output of the MGs can be derived as

$$\frac{P_{\text{MG-1}}}{P_{\text{MG-2}}} = \frac{P^{\text{cap}}_{\text{MG-1}}}{P^{\text{cap}}_{\text{MG-2}}} \rightarrow \begin{cases} P_{\text{MG-1}} = \dfrac{k}{k+1}P_{\text{Load}} \\ P_{\text{MG-2}} = \dfrac{1}{k+1}P_{\text{Load}} \end{cases} \tag{10}$$

where $P_{\text{MG-1}} = \sum_{i=1}^{N_1} P_{\text{DG-}i}$ and $P_{\text{MG-2}} = \sum_{i=1}^{N_2} P_{\text{DG-}i}$ indicate the total power output of the DGs of MG-1 and MG-2 respectively.

Let us define the load-to-capacity (L2C) ratio of an MG as

$$\text{L2C}_{\text{MG}} = P^{\text{Load}}_{\text{MG}}/P^{\text{cap}}_{\text{MG}} \tag{11}$$

Generally, the power flowing through the ISS can be expressed as:

$$P_{\text{Tie-line}} = P_{\text{MG-2}} - P^{\text{Load}}_{\text{MG-2}} \tag{12}$$

Using (10), (12) can be restated as

$$P_{\text{Tie-line}} = \frac{1}{k+1}P_{\text{Load}} - P^{\text{Load}}_{\text{MG-2}} \tag{13}$$

Now, assuming the violation of (7), the following two scenarios are relevant:

- The L2C ratios of the MGs are identical i.e. $P^{\text{Load}}_{\text{MG-1}}/P^{\text{Load}}_{\text{MG-2}} = P^{\text{cap}}_{\text{MG-1}}/P^{\text{cap}}_{\text{MG-2}}$. From (9), hence, the total load of the system can be described as
$$P_{\text{Load}} = (k+1)\times P^{\text{Load}}_{\text{MG-2}} \tag{14}$$
Replacing (14) in (13) concludes that if the MGs have the same L2C ratios, $P_{\text{Tie-line}}$ becomes zero. Thereby, the isolation can be fulfilled with no concern.
- The MGs have non-identical L2C ratios. The following cases may be confronted
$$\begin{cases} 1)\ \mathit{if}\ \ \text{L2C}_{\text{MG-1}} \ge \text{L2C}_{\text{MG-2}} \rightarrow P_{\text{Load}} \ge (k+1)\times P^{\text{Load}}_{\text{MG-2}} \\ 2)\ \mathit{if}\ \ \text{L2C}_{\text{MG-1}} \le \text{L2C}_{\text{MG-2}} \rightarrow P_{\text{Load}} \le (k+1)\times P^{\text{Load}}_{\text{MG-2}} \end{cases} \tag{15}$$
Replacing either of the above cases in (13) yields a non-zero $P_{\text{Tie-line}}$, causing the undesirable disturbances across the ISS at the isolation moment. Note that this unrequired power flows due to the droop-based power sharing of the DGs.

With the aim of achieving the successful disturbance-free isolation, therefore, conduction of an L2C equalization procedure is highly desirable. Assuming $\text{L2C}_{\text{MG-1}} \ge \text{L2C}_{\text{MG-2}}$, accordingly, the total load of MG-2 should be temporarily increased to

$$P^{\text{Temp-Load}}_{\text{MG-2}} = \frac{1}{k}\times P^{\text{Load}}_{\text{MG-1}} \tag{16}$$

such that the mentioned desirable performance ~~fulfills~~is achieved.

The ISS controller is responsible for implementing the isolation action under a decentralized scheme as the system operates based upon a communication-free structure. This means the developed algorithm should be capable of handling the issue by utilizing only the local measurements i.e. $P_{\text{Tie-line}}$ and the frequencies of the MGs. Two ACLs are to be connected at two sides of the ISS in order to temporarily alter the total loads of the MGs. Under normal operation, the load demanded by the ACLs is zero. During the isolation, however, the ACLs should demand a specific amount of power assigned by the controller, balancing the L2Cs of the MGs. With the aim of satisfying (16), the ACL at the MG-2 side of the ISS should raise its demand to

$$P^{\text{Temp-Load}}_{\text{MG-2}} = P^{\text{Load}}_{\text{MG-2}} + P^{\text{ACL}}_{\text{MG-2}} \rightarrow P_{\text{ACL-2}} = \frac{1}{k}\times P^{\text{Load}}_{\text{MG-1}} - P^{\text{Load}}_{\text{MG-2}} \tag{17}$$

The auxiliary demand should be extracted based on only the local measurements. Thus, let us define λ as

$$\lambda = \frac{P_{\text{ACL-2}}}{P_{\text{Tie-line}}} \tag{18}$$

Replacing (13) and (17) in (18) yields

$$\lambda = 1 + 1/k \tag{19}$$

Hence, the derived reference value of the auxiliary demand can be expressed as

$$P_{\text{ACL-2}} = \left(1 + \frac{1}{k}\right)\times P_{\text{Tie-line}} \tag{20}$$

Although the controller is unable to directly measure the total loads of the MGs, (20) can efficiently consider the dynamic of the loads only by measuring $P_{\text{Tie-line}}$.

Eq. (20) is derived assuming $\text{L2C}_{\text{MG-1}} \ge \text{L2C}_{\text{MG-2}}$. Likewise, in case $\text{L2C}_{\text{MG-1}} \le \text{L2C}_{\text{MG-2}}$, $P_{\text{Tie-line}}$ which flows toward MG-2 can be stated as

$$P_{\text{Tie-line}} = \frac{k}{k+1}P_{\text{Load}} - P^{\text{Load}}_{\text{MG-1}} \tag{21}$$

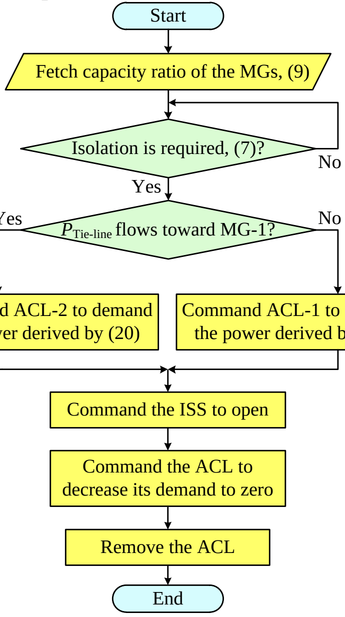


Fig. 3 Flowchart of the developed communication-free approach.

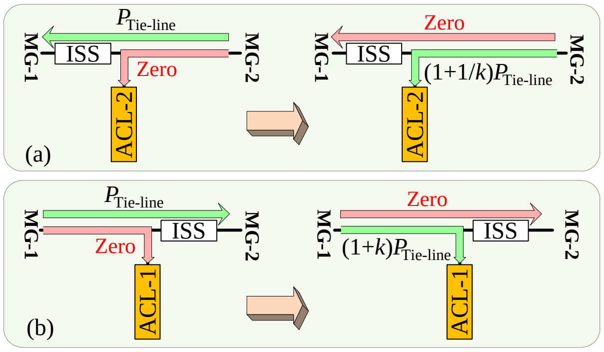


Fig. 4. The power transitions at the ISS by applying the developed approach when (a) $\text{L2C}_{\text{MG-1}} \geq \text{L2C}_{\text{MG-2}}$ and (b) $\text{L2C}_{\text{MG-1}} \leq \text{L2C}_{\text{MG-2}}$.

Therefore, it can be proved that the reference value of the auxiliary demand can be derived as

$$P_{\text{ACL-1}} = (1+k)\times P_{\text{Tie-line}} \tag{22}$$

Once (7) is violated which necessitates an isolation action, the controller utilizes either (20) or (22), depending upon the L2C ratios of the MGs, to calculate the load to be demanded by the ACL, canceling the current flowing through the ISS. Then, the opening of the ISS can be accomplished with no destructive spikes. The flowchart based on which the controller applies the approach is shown in Fig. 3. In addition, Fig. 4 demonstrates the passing power through the ISS both before and after fulfilling the developed scheme. $P_{\text{Tie-line}}$ flows toward MG-1 when $\text{L2C}_{\text{MG-1}} \geq \text{L2C}_{\text{MG-2}}$. By ~~applying~~ thise approach, ACL-2 increases its demand to (20), ~~zeroing~~ forcing the passing current through the tie-line to zero. Fig. 4.b shows the procedure when $\text{L2C}_{\text{MG-1}} \leq \text{L2C}_{\text{MG-2}}$. Raising the demand of ACL-1 to (22) nullifies the ISS current to guarantee a successful isolation.

IV. PERFORMANCE EVALUATION

In order to appraise the performance of the developed approach, several simulation case studies are carried out in PSCAD/EMTDC. Consider the network of Fig. 1 with the structure described in Section II. The detailed technical parameters of the network and the schemes can be found in Appendix. MG-1 consists of three DGs while MG-2 includes two DGs with different load sharing characteristics. Let us assume the ISS has already been closed after satisfying both (4) and (5) due to a sudden power deficiency in MG-1. Then, MG-2 started to provide MG-1 with the required supporting power. Now, by a load decrease in MG-1 at t = 2s, (7) is violated, necessitating an isolation action. The following cases that are based on six different combinations verify the validity of the proposed approach. In the simulation results, the positive and negative signs of $P_{\text{Tie-line}}$ indicate it flows toward MG-1 and MG-2 respectively. For convenience, a three-second time interval is considered between each two consecutive events. In real systems, however, this interval should be adjusted based upon dynamic characteristics of the components.

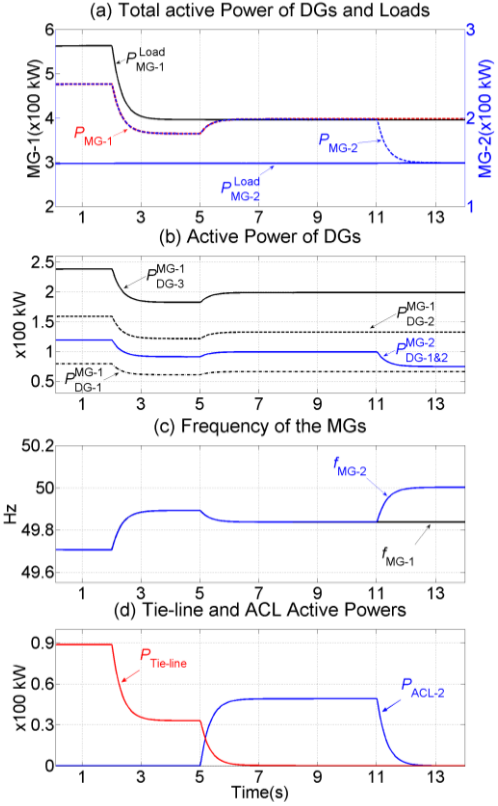


Fig. 5. Simulation results of Case 1.

A. Case 1: $P^{\text{cap}}_{\text{MG-1}} > P^{\text{cap}}_{\text{MG-2}}$ while $\text{L2C}_{\text{MG-1}} > \text{L2C}_{\text{MG-2}}$

In this case, the generation capacities of MG-1 and MG-2 are assumed to be 600kW and 300kW respectively. Initially, the total load of MG-1 is about 570kW. At t = 2s, a 30% load decrease in MG-1 ~~remove~~removings the overloading condition, as can be seen from Fig. 5.a. Fig. 5.b shows the power sharing among the DGs while the frequencies of the MGs are demonstrated in Fig. 5.c. Due to the fact that the L2C ratio of MG-1 is still larger than that of MG-2, a power of about 33 kW flows toward MG-1. Employing (20), thus, the controller commands ACL-2 to increase its demand to 49.5 kW since k = 2. As it is shown in Fig. 5.d, once ACL-2 demands the determined power at t=5s, the L2C ratios of the MGs become identical, successfully dropping the ISS current to almost zero. Then, at t=8s, the controller commands the ISS to open. By accomplishing the isolation procedure, the controller resets ACL-2 to zero at t = 11s. Fig. 6 compares the voltages at the two sides of the ISS with and without applying the proposed scheme. It can be seen that the level of spikes at the opening moment decreases significantly when the scheme cancels the tie-line power prior to the isolation.

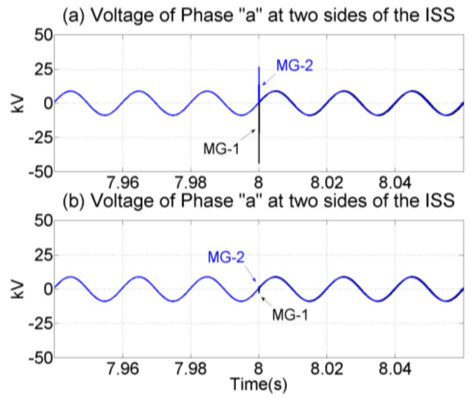


Fig. 6. Voltages at two sides of the ISS at the isolation moment (a) without applying the developed approach, (b) with applying the developed approach.

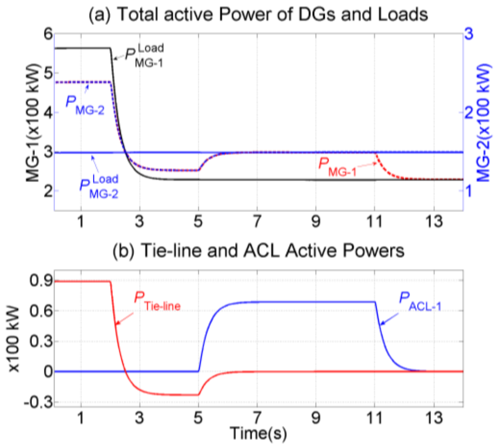


Fig. 7. Simulation results of Case 2.

B. Case 2: $P^{cap}_{MG\text{-}1} > P^{cap}_{MG\text{-}2}$ while $L2C_{MG\text{-}1} < L2C_{MG\text{-}2}$

Let us assume the generation capacities of the MGs are identical to Case 1. Fig. 7.a shows that the power deficiency is resolved following a 60% decrease in the load of MG-1 at t=2s. This causes $L2C_{MG\text{-}2}$ to become larger than $L2C_{MG\text{-}1}$, reversing the direction of $P_{Tie\text{-}line}$, as can be seen from Fig. 7.b. Therefore, the controller utilizes (22) to calculate a demand reference of about 68.5kW for ACL-1 since $P_{Tie\text{-}line}$ is 23 kW. By activating ACL-2 at t=5s, the ISS power drops to zero as desired, yielding a successful isolation action with negligible disturbances at t=8s. Eventually, the isolation procedure is efficiently completed after decreasing the demand of ACL-1 to zero at t = 11s.

C. Case 3: $P^{cap}_{MG\text{-}1} = P^{cap}_{MG\text{-}2}$ while $L2C_{MG\text{-}1} > L2C_{MG\text{-}2}$

In this section, the performance of the approach is evaluated assuming the MGs have identical generation capacities of 600kW i.e. k = 1. The load sharing ratios of the DGs are given in Appendix. Initially, MG-2 supports MG-1 with a power of about 132kW. Fig. 8.a shows that a load decrease of 30% occurs in MG-1 at t=2s, necessitating an isolation action. Since $L2C_{MG\text{-}1}$ is still larger than $L2C_{MG\text{-}2}$, the controller should command ACL-2 to demand the power derived utilizing (20) i.e. 97kW. Fig. 8.b displays that by activating ACL-2 at t=5s, $P_{Tie\text{-}line}$ is desirably canceled as the L2C ratios of the MGs become the same. Then, the MGs are isolate at t=8s. The action is successfully done by removing ACL-2 at t=11s.

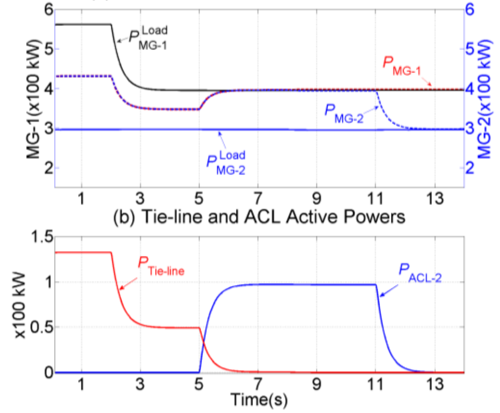


Fig. 8. Simulation results of Case 3.

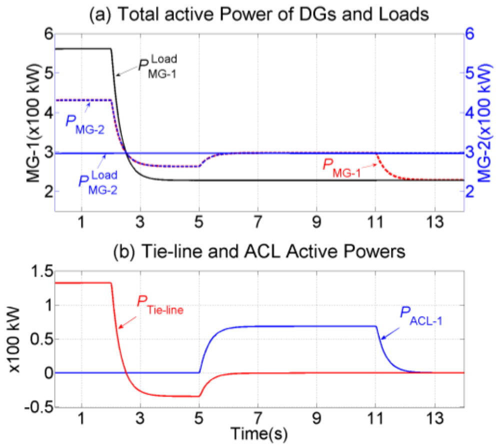


Fig. 9. Simulation results of Case 4.

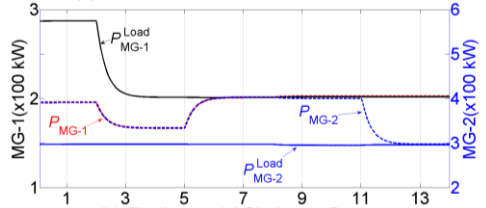
D. Case 4: $P^{cap}_{MG\text{-}1} = P^{cap}_{MG\text{-}2}$ while $L2C_{MG\text{-}1} < L2C_{MG\text{-}2}$

This case considers the MGs of Case 3 with the same initial conditions. The power shortfall of MG-1 is relieved due to a 60% decrease in its total load at t=2s. Consequently, $L2C_{MG\text{-}1}$ becomes smaller than $L2C_{MG\text{-}2}$, as it is observable from Fig. 9.a. Hence, a power of 35kW flows through the ISS to MG-2. With the aim of nullifying this power, ACL-1 demands a power of about 68kW at t=5s, as can be seen from Fig. 9.b. Then, the isolation is efficiently handled by opening the ISS and removing ACL-1 at t=8s and t=11s respectively.

E. *Case 5:* $P_{MG\text{-}1}^{cap} < P_{MG\text{-}2}^{cap}$ *while* $L2C_{MG\text{-}1} > L2C_{MG\text{-}2}$

Let us assume the generation capacities of MG-1 and MG-2 are 300kW and 600kW respectively i.e. k = 0.5. The simulation results are shown in Fig. 10. Initially, the total load demand of MG-1 is 290kW, receiving a supporting power of about 92kW from MG-2. $P_{\text{Tie-line}}$ decreases to about 35kW following a 30% decrease in total load of MG-1 at t=2s. Thus, ACL-2 is commanded to raise its load to about 103kW at t=5s.

(a) Total active Power of DGs and Loads



(b) Tie-line and ACL Active Powers

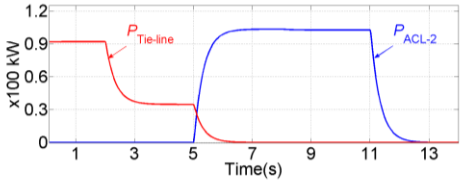
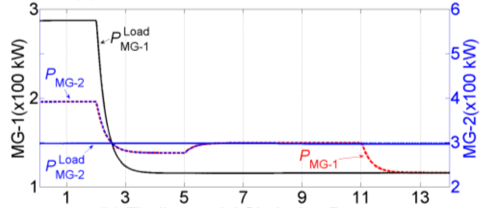


Fig. 10. Simulation results of Case 5.

(a) Total active Power of DGs and Loads



(b) Tie-line and ACL Active Powers

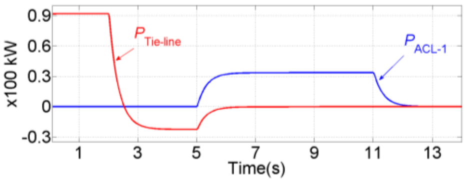


Fig. 11. Simulation results of Case 6.

Since $P_{\text{Tie-line}}$ is successfully dropped to zero, the controller sends a command to the ISS to open at t=8s. Afterward, ACL-2 decreases its demand to zero at t=11s to terminate the action.

F. *Case 6:* $P_{MG\text{-}1}^{cap} < P_{MG\text{-}2}^{cap}$ *while* $L2C_{MG\text{-}1} < L2C_{MG\text{-}2}$

Consider the MGs of Case 5 with the same initial conditions. In this case, however, it is assumed that MG-1 experiences a 60% load decrease at t=2s, thereby reversing the direction of the passing power through the ISS. The simulation results are presented in Fig. 11. According to the developed algorithm, the controller utilizes (22) to extract the load should be demanded by ACL-1. Thus, ACL-1 increases its load to a high of about 33.5kW at t=5s, canceling tie-line current. Following the successful act of ACL-1, the ISS opens at t=8s, with almost no disturbance. Eventually, the controller deactivates the ACL at t=11s to end the algorithm.

V. CONCLUSION

In this paper, a communication-free strategy is proposed to facilitate the isolation action of the coupled microgrids. It is shown that the direction of the flowing power through the tie-line is determined only regarding the load-to-capacity ratios of the MGs. Based on this fact, the powers should be demanded by the auxiliary loads at two sides of the ISS to cancel the tie-line current are accurately formulated. Through various PSCAD simulation studies, it is demonstrated that the scheme can be successfully applied by the ISS controller to fulfill the desired isolation action regardless of the differences in power capacities of the MGs.

TABLE I. TECHNICAL PARAMETERS OF THE MGS.

<table>
<tr><td colspan="7">General parameters:
α =0.1, V_{max} = 6.35 kV, V_{min} = 5.75 kV, f_{max} = 50.5 Hz, f_{min} = 49.5 Hz</td></tr>
<tr><td colspan="7">MGs and CMG line parameters:
Z_{line} = 0.1 + j 0.1 Ω , $Z_{tie\text{-}line}$ = 0.2 + j 0.2 Ω</td></tr>
<tr><td colspan="7">Droop coefficients of MG-1</td></tr>
<tr><td>P^{cap}</td><td colspan="3">600kW</td><td colspan="3">300kW</td></tr>
<tr><td>DGs</td><td>DG-1</td><td>DG-2</td><td>DG-3</td><td>DG-1</td><td>DG-2</td><td>DG-3</td></tr>
<tr><td>m [Hz/kW]</td><td>0.0033</td><td>0.005</td><td>0.01</td><td>0.0067</td><td>0.01</td><td>0.02</td></tr>
<tr><td>n [kV/kVAr]</td><td>0.006</td><td>0.009</td><td>0.018</td><td>0.012</td><td>0.018</td><td>0.036</td></tr>
<tr><td colspan="7">Droop coefficients of MG-2</td></tr>
<tr><td>P^{cap}</td><td colspan="3">600kW</td><td colspan="3">300kW</td></tr>
<tr><td>DGs</td><td>DG-1</td><td colspan="2">DG-2</td><td>DG-1</td><td colspan="2">DG-2</td></tr>
<tr><td>m [Hz/kW]</td><td>0.0033</td><td colspan="2">0.0033</td><td>0.0067</td><td colspan="2">0.0067</td></tr>
<tr><td>n [kV/kVAr]</td><td>0.006</td><td colspan="2">0.006</td><td>0.012</td><td colspan="2">0.012</td></tr>
</table>

ACKNOWLEDGMENT

The authors thank the Australian Research Council (ARC) for the financial support for this project through the ARC Discovery Grant DP140103883.

APPENDIX

The technical parameters of the considered network are listed in Table I.

REFERENCES

[1] M. Arriaga, C.A Canizares and M. Kazerani, “Northern lights: access to electricity in Canada's northern and remote communities,” *IEEE Power and Energy Magazine*, Vol. 12, pp. 50 - 59, 2014.

[2] M.M.A. Abdelaziz, H.E. Farag,, E.F. El-Saadany, “Optimum reconfiguration of droop-controlled islanded microgrids,” *IEEE Trans. on Power Systems*, vol. 31, no. 3, pp. 2144-2153, May 2016.

[3] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with AC and DC subgrids,” *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2214–2223, May 2013.

[4] A. Solanki, A. Nasiri, V. Bhavaraju, Y.L. Familiant, Q. Fu, “A new framework for microgrid management: virtual droop control,” *IEEE Trans. on Smart Grid*, vol. 7, no. 2, pp. 554-566, March 2016.

[5] J. Xiao, L. Bai, , F. Li, H. Liang, C. Wang, “Sizing of energy storage and diesel generators in an isolated microgrid using DFT,” *IEEE Trans. on Sustainable Energy*, Vol. 5, no. 3, pp. 907-916, July 2014.

[6] S.A. Arefifar, Y.A.R.I. Mohamed, T.H.M. EL-Fouly, “Optimum microgrid design for enhancing reliability and supply-security,” *IEEE Trans. on Smart Grid*, vol. 4, no. 3, pp. 1567-1575, Sep 2013.

[7] X. Tang, X. Hu, N. Li, W. Deng and G. Zhang, “A novel frequency and voltage control method for islanded microgrid based on multienergy storages,” *IEEE Trans. on Smart Grid*, vol. 7, no. 1, pp. 410-419, Jan 2016.

[8] Y. Xu, W. Zhang, G. Hug, “Cooperative control of distributed energy storage systems in a microgrid,” *IEEE Trans. on Smart Grid*, vol. 6, no. 1, pp. 238-248, Jan 2015.

[9] R.H. Lasseter, “Smart distribution: coupled microgrids,” *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1074-1082, June 2011.

[10] H. Dagdougui, *et al.* “Optimal control of a network of power microgrids using the Pontryagin’s minimum principle,” *IEEE Trans.*

Control Systems Technology, vol. 22, no. 5, pp. 1942–1948, Sep. 2014.

[11] E. Pashajavid, F. Shahnia, A. Ghosh, “development of a self-healing strategy to enhance the overloading resilience of islanded microgrids,” *IEEE Trans. on Smart Grid*, DOI 10.1109/TSG.2015.2477601.

[12] E. Pashajavid, F. Shahnia, A. Ghosh, “Interconnection of two neighboring autonomous microgrids based on small signal analysis,” 9th International Conference on Power Electronics-ECCE Asia, pp. 213-220, Seoul, Korea, June 1 - 5, 2015.