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A Practical and Intelligent Technique for Coupling Multiple Neighboring Microgrids at the Synchronization Stage

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Abstract—It is expected from a microgrid to supply its local demand independently; however, the load and generation intermittency may lead to overloading of a microgrid temporarily. It is suggested in the literature that this problem can be mitigated by importing the required power from one/more neighboring microgrid(s), after their temporary coupling. This paper focuses on the transition stage of forming a system of coupled microgrids. A suitable and practically applicable strategy is developed in this paper, which facilitates the appropriate connection of the microgrids. The performance of the developed strategy is evaluated by time-domain simulation studies in PSCAD/EMTDC.

Keywords—Coupled microgrids, Overloading management, Synchronization.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>APC</td>
<td>Available power capacity</td>
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<tr>
<td>CMG</td>
<td>Coupled microgrids</td>
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<tr>
<td>DER</td>
<td>Distributed energy resource</td>
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<tr>
<td>IGBT</td>
<td>Insulated gate bipolar transistor</td>
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<tr>
<td>ISS</td>
<td>Interconnecting static switch</td>
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<tr>
<td>OMT</td>
<td>Overload management technique</td>
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<tr>
<td>PDL</td>
<td>Power deficiency level</td>
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<td>PLL</td>
<td>Phase-locked loop</td>
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<td>UPC</td>
<td>Unused power capacity</td>
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1. Introduction

Future distribution networks will include large numbers of distributed energy resources (DERs). This can provide an avenue for a distribution network to be divided into several sections, each with enough generation capacity in its embedded DERs to supply its local demand [1]. Thus, a future distribution network, especially those supplying residential customers, can be considered as a group of neighboring self-sufficient microgrids (MGs) [2], as shown in Fig-1a. Each of these microgrids may have a different operator (owner) that has invested in installing and operating the DERs and supplies a particular group of customers and may operate in islanded mode [3].

The intermittency and output power variations of solar and wind type non-dispatchable DERs in addition to load uncertainties can lead to an imbalance between the instantaneous power generation and demand in a microgrid [4]. Any generation deficiency or excessive demand increase, referred to as microgrid overloading in the rest of this paper, will result in the voltage/frequency deviation of the microgrid. The power imbalance problem
within a microgrid can be addressed in the planning stage by selecting an optimal capacity for its dispatchable DERs (e.g., diesel generators) [5] and battery energy storages [6] or by using either of the below techniques in the operation stage:

- under-voltage/frequency load-shedding [7],
- power exchange by utility feeder and/or battery energy storages [8], or
- coupling of the microgrid to one/more neighboring microgrid(s) [9].

It is to be highlighted that if a utility feeder is available, the safest option for operating an overloaded microgrid is importing power from the utility feeder, after coupling them provisionally. However, such an option is not viable for most of the distribution networks of remote and rural towns [10].

In [11], the concept of coupled microgrids (CMG) is introduced as a solution to proliferate the number of DERs in distribution networks. Under such a concept, each overloaded microgrid in Fig-1b(i) may be supported by one/more of its neighboring microgrid(s). As an example, Fig-1b(ii)-(iv) illustrate three different possibilities when MG-1 of Fig-1b(i) is determined to be overloaded. This option suits well for the remote area distribution networks. Coupling of the neighboring microgrids can be achieved if proper links and normally-open switches are designed and placed between the microgrids.

The conditions that can detect the overloading of a microgrid and the availability of excess power in the neighboring microgrids are developed in [9]. A decision-making-based approach is proposed in [12] to determine the most suitable microgrid(s) when forming a CMG while an optimization-based technique is proposed in [13]. A transformative architecture is proposed for coupling the neighboring microgrids in [14] while [15-16] have aimed to develop an optimal technique for designing the topology of the proper interconnecting lines among the microgrids. Coupling of microgrids can be realized by back-to-back converters [17] or by interconnecting static switches (ISSes) [9] between the adjacent microgrids. The ultimate vision is that a microgrid can be interconnected to any microgrid (and not necessarily an adjacent microgrid) if a general link is available to act as a power exchange highway.

The trade of power among microgrids of a CMG has been discussed in [18] while [19] has evaluated the optimal energy management in CMGs. The cooperative planning of the generated power by the renewable resources within a CMG is proposed in [20] while [21] has proposed energy bidding and pricing mechanism for the traded power between microgrids of a CMG. An interactive control of CMGs is presented in [22] to guarantee effective load sharing and system-wide stability while another control technique is proposed in [23] to prevent a failure in the system following an adversary's action or wrong measurement-initiated attacks to the CMG. Dynamic operation of DERs within CMGs is investigated in [24], and the dynamic security of the CMGs is examined in [25]. Ref. [26-27] have demonstrated how to evaluate the stability of the CMG before its formation, while the interaction among the DERs of the microgrids in a CMG is investigated in [28].
The above studies have focused on either the planning stage of a CMG or the performance of the distribution network and the microgrids before and after coupling. What has not been discussed in the earlier studies is the synchronization of the interconnecting microgrids and the transition stage of moving from a group of isolated islanded microgrids into a CMG system. Although the synchronization of a microgrid to a utility feeder has been analyzed in the literature (e.g. in [29-32]), this transitional stage has not been investigated yet for a CMG formation, especially when it consists of more than two microgrids. This is a critical stage of forming a CMG and needs a dedicated mechanism that prevents unacceptable frequency violations at the transition stage or unintentional overloading of a microgrid. This is the core research gap that is addressed in this paper. Thereby, without a further justification on the benefits of the interconnection of neighboring microgrids or extra discussion on the characteristics of the operation, this paper focuses on developing a suitable and effective technique based on which the selected microgrids are interconnected safely. The developed technique needs to be fast enough such that all interconnections are realized, and a CMG is formed before the operation of under-voltage/frequency protective relays. To this end, a generalized algorithm is developed and validated in this paper and aims to connect the selected microgrids, when forming a CMG. The algorithm is validated by time-domain simulation studies in PSCAD/EMTDC. The main contributions of this research are:

- to develop a suitable and practically applicable strategy for the transition stage of coupling the microgrids,
- to develop an appropriate local control system for the ISSes between the microgrids, and
- to validate the feasibility of the developed strategy.

The rest of the paper is organized as follows: The technique based on which the suitable microgrids of a distribution network are selected to couple, in order to support the overloaded microgrid(s), is briefly discussed in Section-2. Section-3 presents the proposed control for the ISSes. The developed synchronization strategy is introduced in Section-4 while Section-5 highlights some data communication considerations for this technique. The performance evaluation results of a distribution network with the developed technique, operating under different conditions, are presented in Section-6 while the general conclusions of the research are highlighted in the last Section. Appendix-A briefly presents the considered structure for the ISSes within the simulation studies.

2. Selection of Microgrids to Form a CMG

Let us consider the distribution network of Fig-1a with $N$ islanded microgrids, among which $N$’ microgrids are assumed to be overloaded. Each of the non-overloaded microgrids may be able to support the overloaded microgrids individually or in combination. A suitable and effective overload management technique (OMT) is proposed by the authors in [12] in which the OMT is located as a module within the distribution network controller (i.e., system tertiary controller) and continuously communicates with the central controller of each microgrid to calculate the available power capacity (APC) for MG-$i$, $i \in \{1, \ldots, N\}$, defined as
\[ APC_{\text{MG-}i} = \left(1 - \alpha\right) \sum_{\text{disp-DER(MG-}i)} P_{\text{disp-DER(MG-}i)}^{\text{max}} - \sum_{\text{disp-DER(MG-}i)} P_{\text{disp-DER(MG-}i)} / \sum_{\text{disp-DER(MG-}i)} P_{\text{disp-DER(MG-}i)}^{\text{max}} \] (1)

where \( \sum_{\text{disp-DER(MG-}i)} P_{\text{disp-DER(MG-}i)}^{\text{max}} \) and \( \sum_{\text{disp-DER(MG-}i)} P_{\text{disp-DER(MG-}i)} \) represent respectively the aggregated active power output and the aggregated capacity of dispatchable DERs in MG-\( i \) and \( 0 < \alpha < 1 \) (e.g. \( \alpha = 0.1 \)) imposes a safety margin. APC can be called the unused power capacity (UPC) of a microgrid when \( APC > 0 \) while its magnitude is the power deficiency level (PDL) of the microgrid when \( APC < 0 \). It is desired to maintain the UPC of every microgrid higher than a threshold, such as

\[ UPC_{\text{MG-}i} > 0 \] (2)

If (2) is valid for all microgrids, no action needs to be taken. However, if it is invalid for one or more microgrids, those microgrids are defined as the 'overloaded microgrids,' and the OMT evaluates the availability of surplus power in the network from

\[ \sum_{i=1}^{N} UPC_{\text{MG-}i} > \sum_{i=1}^{N} PDL_{\text{MG-}i} \] (3)

If (2) flags the overloading of one/more microgrid(s), and (3) flags the unavailability of surplus power in the distribution network, the OMT has no other option except proceeding to apply load-shedding in the overloaded microgrid(s). However, if (3) flags the availability of surplus power in the distribution network, the OMT will proceed to support the overloaded microgrid(s) by coupling one/more of the non-overloaded microgrid(s) with the overloaded one(s).

Let us call the non-overloaded microgrid(s) that are selected by the OMT as the 'selected microgrid(s).’ Coupling of the selected microgrid(s) to the overloaded one(s) can be achieved by closing the relevant ISSes. Before initiating a command to couple the neighboring microgrids, the stability of the CMG should be cautiously evaluated, as discussed in [26-27]. The stability analysis should also evaluate whether the overloaded microgrid(s) may become unstable before the connection of the selected suitable neighboring microgrid(s). Indeed, the CMG formation will not proceed if such instability issues are detected. Therefore, in the rest of this paper, it is assumed that the OMT has detected the overloaded microgrid(s), has defined the selected microgrid(s) and has validated the stability of the considered CMG, as well as the stability of the overloaded microgrid(s) in the stage of interconnection. It is only at this last stage that the proposed strategy in this paper initiates its operation (as illustrated schematically in the flowchart of Fig-1c) while the analyses of the OMT to determine the overloaded microgrid(s) and define selected microgrids (illustrated in the early steps of the flowchart are presented and evaluated in [12] and are not repeated here).

The following considerations should be taken into account about the OMT and the research scope of this paper:

1- Proper modifications are necessary to prevent the central controllers of the microgrids of the CMG from fighting against each other for voltage and frequency adjustment after they are coupled. This needs further de-
2- The formed CMG is desired to divide into the isolated microgrids eventually if the overloading of the microgrid(s) is eliminated, or if the CMG system gets overloaded because of a significant decrease in the renewable-based generation of its microgrids or a significant demand increase in one of the participating microgrids. In such a circumstance, the existing CMG should be divided into the contributing microgrids, and another suitable CMG should be formed (if possible), or the loads in the overloaded microgrid(s) should be shed. The isolation of microgrids does not need a synchronization process and can be conducted as immediately as it is required, according to the developed criteria in [9]. As this paper focuses on the interconnection stage of microgrids, their isolation is not discussed here.

3- The power generated by non-dispatchable DERs may change rapidly due to their intermittency. Thus, a microgrid status may frequently change from normal to overloaded and vice versa. Using the dead-band limits in defining the overloading and normal conditions of a microgrid, the coupling and isolation of microgrids will be limited to the most severe cases only.

3. Developed Control for the ISS

The microgrids can be coupled with the help of ISSes. The structure of an ISS is beyond the scope of this research. However, a brief description of the structure and operation mechanism of the considered ISS in this research is presented in Appendix-A. Each ISS has a local controller, illustrated schematically in Fig-1d. It starts conducting based on the closing and synchronization commands that it receives from the synchronization module (SM), an agent located within the distribution network controller which facilitates the synchronization and interconnection of the microgrids, and stops conducting when receiving the opening command from the OMT. The controller also observes the status of the ISS and sends a closing confirmation (CC) signal to the synchronization module, whenever it closes. It is to be highlighted that the ISS controller receives and transmits this information to the central controller of the relevant microgrid and does not directly communicate with the distribution network controller to obey the system hierarchical control aspects. Fig-1e illustrates the schematic diagram of the communication links that are required for low-bandwidth data communication among the distribution network controller (i.e., the OMT and synchronization module), the central controller of each microgrid, and the local controller of each ISS.

In the control block diagram of Fig-1d, two phase-locked loops (PLLs) are used to determine the frequency and angle of the voltages appearing at two sides of the ISS. Thus, their design is of significant importance. Some PLLs may have performance degradation when the frequency of the system changes, which is very crucial for microgrid applications. In this study, a frequency-insensitive, positive sequence fundamental component detection method is used [33]. For this purpose, the considered PLL system first identifies the frequency of the system and then derives the positive sequence component of the waveform in the actual frequency of the system from which the waveform
angle is then calculated. Alternatively, PLLs with structures proposed in [34-35] may be used. It is to be noted that in reality, even when same types of PLLs are used, if their internal parameters mismatch, a frequency and phase deviation between two PLLs may be observed. Thus, designing the PLL structure (which is beyond the scope of this research) can be elaborated in details as a future research avenue to result in successful, accurate and fast operation even when significant harmonic distortions or frequency changes are observed in the voltage waveforms of the microgrid.

Before the interconnection of any two microgrids, each microgrid may have a different voltage and frequency. Thereby, an important stage of forming a CMG is the synchronization of the interconnecting microgrids. In this research, synchronization is referred to as the connection process of a microgrid to a neighboring microgrid through an ISS. The connection should only take place once the difference of instantaneous voltages and voltage angles across the ISS are zero (or lower than a small specified value) [29]. The inappropriate connection may cause high current fluctuations which can damage the network assets or result in system instability. The ISS closing consists of a synchronization process, after which a CMG is formed. Different synchronization methods are proposed in [30-32]. Additionally, some other techniques such as the ones presented in [36-37] can be used to speed up the synchronization process. In this research, a normal (non-forced) synchronization procedure is utilized. Hence, the ISS closes once the difference of two instantaneous voltages at either side of the ISS (i.e., \(|\Delta v| = |v_{MG,1}(t) - v_{MG,2}(t)|\)) becomes smaller than \(\varepsilon_v\) and the difference of their angles (i.e., \(|\Delta \delta| = \left| (2\pi f_{MG,1}t + \theta_{MG,1}) - (2\pi f_{MG,2}t + \theta_{MG,2}) \right| \)) becomes smaller than \(\varepsilon_\delta\) (e.g., \(\varepsilon_v = \varepsilon_\delta = 0.001\) pu) [38], only if its local controller has received the synchronization command. It is to be noted that function \(||\) above denotes the absolute function. This is schematically shown in the proposed logic diagram of the local controller of the ISS in Fig-1d. Appendix-B provides a discussion and a general guideline about the expected synchronization period. It is noteworthy that in reality, a continuous change may be observed in the magnitude and frequency of the voltages at either side of the ISS (depending on the generation-demand imbalance in a microgrid) between the times that the synchronization command is received until the synchronization is realized. Due to such variations, it is very hard to develop a mathematical approach to predict the synchronization period in real systems. Thereby, the developed algorithm in this paper is designed to be independent of any calculations, thus makes it practically implementable for real systems.

The main limitation of the considered normal synchronization procedure is that it will take a long time if the frequency difference of two microgrids (\(|\Delta f|\)) is small. If a selected microgrid is to be connected to an overloaded microgrid (which experiences a frequency close to the minimum acceptable frequency), there will be a non-negligible \(|\Delta f|\) between them. Thus, normal synchronization will not be a problem. However, if two selected microgrids are to be coupled before being interconnecting with the overloaded microgrid, they may exist some rare conditions in which their \(|\Delta f|\) is too small. In such cases, a forced synchronization is unavoidable. To this end, the
local controller of an ISS sends a notification signal (via transmitter-2 of Fig-1d) to the central controller of the microgrid when it detects a $|\Delta f|$ of less than $\varepsilon_f$ (e.g., $\varepsilon_f = 0.01$). The central controller of the microgrid then enables an activation signal to one of its DERs to slightly and temporarily reduce the set-point of its frequency ($f_{\text{set-point}}$) as

$$f_{\text{set-point}}^{\text{new}} = f_{\text{set-point}}^{\text{old}} - \gamma$$

where $0 < \gamma < 1$ (e.g., $\gamma = 0.02$) such that $|\Delta f|$ becomes larger than $\varepsilon_f$. If so, the ISS closes after synchronization, and the set-point resets to the initial value, immediately after the closing of the ISS. As this stage falls into the local controller of a DER, it is not elaborated more here.

It is to be reminded that the ISS opening signal is directly issued by the OMT, and the ISS opens immediately after receiving this signal. To enable the safe operation of a CMG, each ISS is suggested to be equipped with a backup control system, which forces an ISS to open only if the data communication system failure is detected, while the frequency of the CMG ($f_{\text{CMG}}$) falls below $f_{\text{CMG}}^{\text{min}}$ where

$$f_{\text{CMG}}^{\text{min}} = (1 + \lambda)f_{\min}$$

in which $0 < \lambda < 0.02$ (e.g., $\lambda = 0.001$) and $f_{\min}$ is the minimum acceptable frequency in the distribution network (e.g., $f_{\min} = 49.5$ Hz in a system with a nominal frequency of 50 Hz). This back-up control is also seen in Fig-1d.

It is to be noted that conventional circuit breakers or synchro-checks with the added communication protocol can also be used instead of a power electronics-based ISS. In this context, selection of a specific type of switching device will not affect the principles of the proposed synchronization strategy (the main contribution of this research). However, it is noteworthy that the main benefit of the ISSes versus conventional circuit breakers is that they are fast. An ISS can start/stop conducting in less than a few milliseconds that is the required time for turning on/off its insulated gate bipolar transistor (IGBT) while this time is in the range of 10-100s of milliseconds for conventional circuit breakers.

4. Developed Synchronization Strategy of Multiple Microgrids

In general, synchronization of the neighboring microgrids highly depends on the existing physical links (distribution lines) between the microgrids. Let us assume 4 probable interconnection schemes as below:

- **Scheme-1**: all microgrids are connected to a central node (bus) through individual links (see Fig-2a),
- **Scheme-2**: all microgrids are attached to a radial or loop line (see Fig-2b-c),
- **Scheme-3**: a physical link is available between every two microgrids (see Fig-2d),
- **Scheme-4**: a physical connection exists among some of the microgrids (see Fig-2e).

Depending on each of the above systems, a suitable synchronization procedure should be employed. Among the above schemes, scheme-1 and 2 do not have any difference from the synchronization point of view and are treated equally. This paper only focuses on these two schemes. It is noteworthy that scheme-3 has numerous options for synchronization while forming a CMG. In general, since it is desired to form the CMG as soon as possible to limit
the duration of non-standard voltage/frequency drop in the overloaded microgrid(s), an artificial intelligence or optimization-based technique can be developed to determine which microgrids should be connected first (in the transition stage) so that the overloaded microgrid is relieved quicker. However, development of a suitable technique for this purpose is a technical challenge and can be the scope of a future publication. Scheme-4 has limited options and probably, depending on the physical links of the overloaded microgrid with the other microgrids, one or more options may be available during the synchronization procedure. It is to be noted that this paper does not aim to define the best scheme among those of Fig-2, as it is a planning stage research, and their optimal design has been discussed from cost and reliability perspectives in [15-16] and from stability perspective in [28] while a graph theory-based technique is used in [39-40] for this purpose.

Now let us consider either of the distribution networks of Fig-2a-c. The developed synchronization strategy is in the form of an autonomous agent, referred to as the synchronization module, which only gets activated when the OMT has selected the suitable microgrids to be coupled with the overloaded ones and has validated the CMG stability. Let us assume that the OMT selects $M$ microgrids to be coupled with $K$ overloaded microgrids. Considering the fact that it is desired to minimize the appearance of non-standard voltage/frequency in the overloaded microgrid(s), the objective of the developed synchronization strategy is to interconnect at least one of the selected microgrids with the overloaded microgrid(s) as soon as practically possible. This will be followed by the connection of the other selected microgrids to them. To this end, there must be at least one microgrid among the selected $M$ microgrids that can solely supply the PDL of one/more of $K$ overloaded microgrid(s) without being overloaded. Let us call such selected microgrids as ‘self-sufficient microgrids.’ To determine them, the synchronization module first compares the PDL of the overloaded microgrid(s) with the UPC of each selected microgrid and then determines self-sufficient microgrids as those selected microgrids that satisfy

$$\text{UPC}_{\text{MG},j} \geq (1 + \beta) \text{PDL}_{\text{MG},j}, \quad \forall \quad i \in \{1, 2, \ldots, M\} \quad j \in \{1, 2, \ldots, K\}$$

(6)

and eventually, lists them under vector $SS$. In (6), $0 < \beta < 1$ (e.g., $\beta = 0.05$) is a small dead-band to compensate for any losses in the interconnecting lines between the microgrids. At this stage, the synchronization module selects the microgrid within $SS$ that has the highest UPC and calls it MG-ss. It then lists the overloaded microgrid(s) that can be fully supplied by MG-ss within vector $P$. MG-ss should be able to supply all microgrids within $P$ simultaneously when they form a temporary CMG. The synchronization module then sends an instantaneous closing command to the ISS of the first microgrid within $P$. Closing of this ISS occurs immediately since the outgoing side of the ISS is not energized (To prevent an instantaneous closing if the outgoing side the ISS is energized, the local controller of the ISS checks the voltage difference across the ISS when receiving a closing command, as seen from Fig-1d). When closed, the ISS sends a closing confirmation signal to the synchronization module. As soon as the synchronization module receives this signal, it sends a command to the ISSes of other microgrids within $P$ as well.
as the other **selected microgrids to synchronize with the current CMG.** As soon as their ISSes receive the command, they initiate the synchronization procedure. The ISS of each of these microgrids close and they couple with the existing CMG as soon as they are synchronized. Whenever the synchronization module receives a closing confirmation signal from the ISS of a selected microgrid, it evaluates the possibility of interconnecting the existing temporary CMG with one or more overloaded microgrids which are not within P, denoted by MG-\(l\), that satisfy

\[
\sum_{E_{\text{Existing CMG}}} \text{UPC}_{\text{MG-}i} \geq (1 + \beta) \left( \sum_{E_{\text{Existing CMG}}} \text{PDL}_{\text{MG-}j} + \text{PDL}_{\text{MG-}l} \right) \forall j \in P
\]

\[
\sum_{L \in \{1', 2', ..., K\}, l \notin P} \text{PDL}_{\text{MG-}l} 
\]

(7)

If the synchronization module detects that one/more MG-\(l\) satisfy (7), it will send a synchronization command to its/their ISS(es). This process continues until all overloaded microgrids are connected to the selected microgrids. As an example, let us assume that the OMT has selected 5 microgrids to connect to an overloaded microgrid. Let us also assume that 3 of them are defined to be self-sufficient from (6). Fig-3a illustrates the operation sequence of the developed synchronization module for this case schematically. As a second example, let us assume the OMT has selected 4 microgrids to connect to 4 overloaded microgrids. Let us also assume one of these microgrids can solely supply two of the overloaded microgrids. It is also assumed that any three non-overloaded microgrids can supply all overloaded microgrids. Fig-3b illustrates schematically the operation sequence of the developed synchronization module for this case.

The synchronization module may define that no selected microgrids can solely supply the PDL of the overloaded microgrid(s). In such a case, it defines the two-microgrid combinations from the list of the selected microgrids that can satisfy (6) together. Let us call those as the ‘self-sufficient two-microgrid combinations.’ The synchronization module then aims to select one of those self-sufficient two-microgrid combinations. It is desired that the selected two-microgrid combination fulfills either of the objectives of:

- **Objective-1:** a two-microgrid combination which synchronizes quicker than other two-microgrid combinations,
- **Objective-2:** a two-microgrid combination where the total synchronization period (i.e., between the two microgrids, and between the overloaded microgrid with them) is minimum,
- **Objective-3:** a two-microgrid combination with the highest combined UPC versus others.

Objective-1 guarantees that the selected two-microgrid combination will be formed quicker than the other two-microgrid combinations; however, there is no guarantee that the total synchronization period with the overloaded microgrid will be the minimum (as it is possible that another two-microgrid combination with a larger synchronization period may synchronize with the overloaded microgrid quicker). Although objective-2 is the most desired one, development of a fast and accurate calculation technique is very challenging. This is because the synchronization module needs to precisely calculate the synchronization period of the microgrids in every two-microgrid
combination and define the angle of the voltage at that time. It then needs to recalculate the synchronization period of the overloaded microgrid with that two-microgrid combination. This fast and exact time calculation and the calculation of the corresponding voltage angles at that time is the primary technical barrier in deploying an optimization-based technique. Thereby, in this research, it is assumed that objective-3 is the most practical option, and thus, it has been utilized in the developed strategy.

When a two-microgrid combination is selected, the synchronization module lists the microgrids that constitute the selected two-microgrid combination under vector SS. It also lists the overloaded microgrid(s) that can be adequately supplied by the selected two-microgrid combination, within a temporary CMG, under vector P. Then, the synchronization module sends a command to the ISS of the first microgrid listed within SS to close instantly. As soon as the synchronization module receives the closing confirmation signal from that ISS, it sends a command to the ISS of the other microgrid listed within SS to synchronize with that. On receipt of the closing confirmation signal, the synchronization module initiates a synchronization command to the ISS of all overloaded microgrids listed within P. It also sends a synchronization command to the ISSes of all remaining non-overloaded selected microgrids. As soon as the synchronization module receives the closing confirmation signal from one of the remaining non-overloaded selected microgrids, it conducts the evaluation of (7) to detect whether any overloaded microgrids that are not listed under P can be supplied in the existing temporary CMG. If so, it sends a synchronization command to those overloaded microgrids. This procedure continues until all overloaded microgrids are connected to the selected microgrids. As an example, let us assume the OMT has selected 4 microgrids to be connected to an overloaded microgrid. It is also assumed that neither of them is capable of supplying solely the overloaded microgrid based on (6) while a two-microgrid combination can supply it. Fig-3c illustrates the operation sequence of the developed synchronization module for this case schematically.

If the synchronization module fails to define two-microgrid combinations, it looks for determining x (i.e., respectively 3, 4 and more) microgrid combinations that together satisfy (6). The same procedure discussed above will continue until all selected microgrids by the OMT are coupled with the overloaded microgrids. As an example, Fig-3d illustrates schematically the operation sequence of the developed synchronization module when a 4-microgrid combination can satisfy (6) for a CMG of 5 microgrids. The algorithm of the developed strategy is shown in Algorithm-1.

5. Communication System Considerations

The proposed synchronization strategy only needs a communication link between the central controllers of the microgrids to the system tertiary controller (see Fig-1e). Assuming that the distribution network has already such a tertiary controller (which is highly probable for a multi-microgrid system with a hierarchical control [3]), there is no need for extra communication systems and only a few new low-bandwidth data will be transmitted through the existing link.
The proposed strategy, similar to all communication technology-based strategies and systems, is vulnerable to the communication link failure. For the system of Fig-1e, a communication failure may affect:

- all communication links, or
- only the communication link between the local controller of the ISS and the central controller of a microgrid, or between the central controller of a microgrid and the distribution network controller.

The first failure may avoid the proper operation of the OMT and thus, the CMG formation, following the overloading of a microgrid, due to the lack of data from microgrids. The second failure is limited to data transmission failure of the closing and synchronization commands and the closing confirmation signals. In this case, the CMG will not be formed if the communication failure is in the links of one of those microgrids that are to form a CMG. It is, however, to be noted that after both of the above failures, the central controller of the overloaded microgrid will proceed to shed a portion of its loads, as was a normal operational strategy before the development of the concept of coupling neighboring microgrids. Thus, it will not impose any instability issues. It is to be highlighted that this is the normal expectation from every communication-based system, and indeed, designing communication systems with better reliability and contingency will minimize the failure possibility.

It is also possible to assume that a data communication mismatch occurs when any signal is transmitted within the system of Fig-1e. To rectify this problem, transmitters normally continue to transmit the signal in periods of $T$ (e.g., $T = 300$ ms) until a data receipt (DR) signal is received from the relevant receiver [41]. This was considered in the block diagram of the ISS controller in Fig-1d and if the transmitter fails to get a data receipt signal after $X$ transmissions (e.g., $X = 30$), a communication system failure flag turns on.

6. Performance Evaluation

To evaluate the feasibility of the developed synchronization strategy, the distribution network of Fig-2a is modeled with $N = 6$ microgrids in PSCAD/EMTDC where the technical data of the microgrids, DERs, and voltage source converter models are provided in [9, 12]. The aggregated maximum capacity of the dispatchable DERs of each microgrid is assumed to be 300 kVA (i.e. 1 pu), while their demands and generations of DERs are different. Several study cases are considered, six of which (i.e., case-1 to case-6) discussed below. Table-1 summarizes the UPC and PDL of each microgrid and highlights the overloaded microgrid(s), selected microgrids, and the self-sufficient microgrid(s). Different CMGs are desired in each study case, as provided in Table-1. It is to be highlighted that this section does not aim to evaluate and present general steady-state and dynamic study results as theses characteristics are already evaluated in [9, 12]. It only focuses on evaluating the performance of the developed synchronization strategy in properly coupling the microgrids in the transition stage (the main contribution of this research).

In the below studies, the demand variation in a microgrid, which has resulted in its overloading, is also not illustrated. Thus, $t = 0$ shows the time that the OMT has detected the overloading in the microgrid(s), has decided on the suitable microgrids to form a CMG, and has checked its stability. At this time, the frequency of the overloaded
microgrid in each case (except Case-5) is assumed to be 49.65 Hz; however, after the formation of the desired CMG, their frequency rises up, as listed in Table-1. Furthermore, neither communication delay nor any communication data mismatches are considered in these studies. The frequencies of the participating microgrids in the CMGs of Case-1 to Case-6, as well as the open/close status of their ISSes, are shown in Fig-4a-f. Table-2 summarizes the time-sequence of the events in each study case.

A. Scenario-A

First, let us assume that MG-3 is overloaded, and MG-1 and MG-2 are the selected microgrids by the OMT to support MG-3. In Case-1, it is assumed that the UPC of MG-1 is higher than the PDL of MG-3 while this is not valid for MG-2. Thus, the synchronization module couples MG-1 with MG-3 before connecting MG-2. In Case-2, it is assumed that the UPC of neither MG-1 nor MG-2 is higher than the PDL of MG-3 while their combined UPC is greater than that. Thus, the synchronization module selects a two-microgrid combination (i.e., MG-1 and MG-2) and couples them before connecting MG-3.

B. Scenario-B

Now, let us assume that MG-5 is overloaded, and MG-1 to MG-4 are selected by the OMT to form a CMG. In Case-3, it is assumed that the UPC of MG-1 is higher than that of MG-2, and the UPC of both of them is greater than the PDL of MG-5. However, the UPC of MG-3 and 4 is less than the PDL of MG-5. Thus, the synchronization module couples MG-1 with the MG-5 and then initiates a synchronization command to MG-2, MG-3, and MG-4. In Case-4, it is assumed that the UPC of all selected microgrids is less than the PDL of MG-5. Thereby, the synchronization module lists the two-microgrid combinations that can supply MG-5. Among them, the synchronization module recognizes that the two-microgrid combination of MG-1 and MG-2 has the highest UPC. Thereby, the synchronization module couples MG-1 with MG-2 first and then initiates a synchronization command to MG-3, MG-4, and MG-5.

C. Scenario-C

Now, let us assume that two overloaded microgrids are detected. In Case-5, it is assumed that MG-4 and MG-5 are overloaded, and MG-1 to MG-3 are selected by the OMT to support them. The UPC of MG-1 is higher than the PDL of both MG-4 and MG-5 and the UPC of MG-2 is greater than the PDL of MG-4. Thereby, the synchronization module selects MG-1 (the self-sufficient microgrid with the highest UPC) to be coupled with MG-5 (the overloaded microgrid with the highest PDL). It then initiates a synchronization command to MG-2 and MG-3 (the remaining selected microgrids). If either of them is coupled and the existing temporary CMG can supply MG-4 (the remaining overloaded microgrid), it initiates a synchronization command to that. In Case-6, MG-5 and MG-6 are overloaded, and MG-1 to MG-4 are selected by the OMT to form a CMG. Neither of the selected microgrids can solely support the overloaded microgrids. Thereby, the synchronization module lists the self-sufficient two-microgrid combinations and selects the combination composed of MG-1 and MG-2, as it has the highest UPC. It then sends a synchronization command to MG-6 (the overloaded with the highest PDL) as well as MG-3 and MG-4 (the remaining se-
lected microgrids). If either of MG-3 or MG-4 is coupled and the existing temporary CMG can supply MG-5 (the remaining overloaded microgrid), it initiates a synchronization command to that.

7. Conclusion

Interconnection of multiple neighboring microgrids needs a suitable synchronization technique which depends on the topology of the existing physical links among the microgrids. This paper has presented an appropriate synchronization strategy to be used at the transition stage of forming a system of coupled microgrids when they are coupled through a central bus or line. The developed algorithm, used as an agent within the distribution network controller, manages the connection of the microgrids and uses a low-bandwidth data communication between the central controllers of the microgrids and the distribution network controller. In this strategy, normal synchronization of any two microgrids is the preferred technique and forced-synchronization is limited to conditions in which the frequency difference between the two interconnecting microgrids is small. The developed strategy aims to reduce the duration of non-standard voltage/frequency in the overloaded microgrid(s) while preventing temporary overloading of the participating microgrids in the transition stage. Development of a synchronization strategy for a distribution network in which a physical link is available between every two microgrids or few links exist between them can be a future research topic.

As highlighted before, the interconnection of microgrids is allowed if not only the steady-state stability of the CMG is guaranteed, but also the overloaded microgrid(s) do not become unstable in the synchronization stage (i.e., prior to the CMG formation). The criteria based on which this issue is determined can be developed as a future research topic.

Appendix-A: The ISS Structure

Microgrids can be coupled by the help of ISSes. Fig-A1 illustrates the probable per-phase structure of two ISSes. The structure of Fig-A1(i), composed of an insulated gate bipolar transistor (IGBT) within a diode bridge, is used in the simulation studies of this research. It is to be highlighted that this figure illustrates the structure of the ISS, and obviously, depending on the current and voltage capacity of each IGBT and diode and the system requirements, more IGBTs, and diodes may need to be connected in series and/or in parallel. In this structure, when the IGBT is turned on, a bi-directional sinusoidal current can flow through the ISS where only two forward-biased diodes conduct in each half-cycle. The microgrids will be isolated as soon as the IGBT is turned off. Therefore, this ISS has a less complicated switching control system versus the structure of Fig-A1(ii) which needs continuous turn on/off signals for each IGBT in each half-cycle. Moreover, the IGBT in the structure of Fig-A1(i) has only conduction losses and no continuous switching losses. However, the diodes have conduction as well as switching losses. A detailed economic analysis of these two structures can yield the most suitable economic structure for the ISSes in future research.

Appendix-B: Calculation of Synchronization Period
To discuss the practical implementation stage of the developed synchronization strategy, let us assume that the local controller of the ISS receives the closing command at \( t = 0 \). In such a case, the voltages on MG-1 and MG-2 side of the ISS will be in phase with each other and synchronize at \( t_{\text{sync}} \) if

\[
2\pi f_{\text{MG-1}} t_{\text{sync}} + \theta_{\text{MG-1}} = 2\pi f_{\text{MG-2}} t_{\text{sync}} + \theta_{\text{MG-2}} + k \pi
\]  

(B1)

where \( f_{\text{MG-1}} \) and \( f_{\text{MG-2}} \) are respectively the frequency of MG-1 and MG-2 while \( \theta_{\text{MG-1}} \) and \( \theta_{\text{MG-2}} \) are the phases of the voltage of MG-1 and MG-2 side of the ISS when it receives the synchronization command. \( k = 0, \pm 2 \) is determined based on the different values of \( \Delta \theta = \theta_{\text{MG-1}} - \theta_{\text{MG-2}} \) and \( \Delta f = f_{\text{MG-1}} - f_{\text{MG-2}} \) by taking into account which voltage is leading/lagging the other one and when their possible synchronization will be from

\[
k = \begin{cases} 
+2 & \Delta \theta \leq 0 \text{ and } \Delta f > 0 \\
0 & \Delta \theta \neq 0 \text{ and } \Delta \theta \Delta f > 0 \\
-2 & \Delta \theta \geq 0 \text{ and } \Delta f < 0
\end{cases}
\]  

(B2)

From (B1), the required synchronization period can be expressed as

\[
t_{\text{sync}} = (k \pi - \Delta \theta) / 2\pi \Delta f
\]  

(B3)

The actual synchronization period may be slightly (i.e., less than half a cycle) larger than \( t_{\text{sync}} \) so that \( |\Delta v| \) also becomes smaller than \( \varepsilon_v \). As an example, Fig-B1a shows the instantaneous phase-a voltage at either side of an ISS when a synchronization command is received. Based on the assumed voltage angle and frequency difference between these voltage waveforms at this time, from (B3), the synchronization period is found to be \( t_{\text{sync}} = 0.562 \) s. Fig-B1b illustrates the two voltages at either side of the ISS a few cycles before and after the synchronization. Fig-B1c illustrates the instantaneous difference between two voltage waveforms of Fig-B1b while Fig-B1d illustrates the current passing through the ISS at the synchronization time. As seen from this figure, no significant switching transients are imposed to either of the microgrids because the ISS closes when the voltage difference across the ISS is negligible.

Fig-B2a shows the required synchronization period as a function of \( \Delta \theta \) for \( 0.2 \leq \Delta f \leq 1 \) Hz. It can be seen from this figure that for each \( \Delta f \), the synchronization period increases linearly as \( \Delta \theta \) increases. Fig-B2b shows the required synchronization period as a function of \( \Delta f \) for \( \pi/4 \leq \Delta \theta \leq \pi \) rad. It is seen from this figure that for each \( \Delta \theta \) the required synchronization period increases as \( \Delta f \) decreases. Fig-B2c–d illustrate a 3D diagram of the required synchronization period versus different positive and negative values of \( \Delta f \) and \( \Delta \theta \). In this figure, two discontinuities can be observed. The first discontinuity is for \( 0.5 < \Delta f < 0.6 \) Hz which is because at this range of frequency, the synchronization period is very small versus any other smaller or larger frequency differences due to the impact of \( k \). The second discontinuity is for \(-0.1 < \Delta \theta < 0.1 \) rad which is due to the fact that the synchronization period becomes large as also seen in Fig-B2b.

In deriving (B3), for simplification, it is assumed that the differences in magnitude and frequency of the voltages
at two sides of the ISS remain constant throughout the synchronization period. However, in reality, a continuous change may be observed in the voltage magnitude and frequency depending on the generation-demand imbalance in a microgrid. Nevertheless, this only results in the synchronization period to be slightly shorter or longer than that given by (B3) and it does not have a significant impact on the operation principle of the ISS. It is to be highlighted that due to such variations, it is very hard to develop a mathematical approach to predict the synchronization period in real systems. Thereby, the developed algorithm in this paper is designed to be independent of any calculations to make it practically implementable. Again it is to be noted that (B3) is presented here as a guideline only to calculate approximately the expected synchronization period and it is not a new method nor has it been used in the developed strategy in this research.

References


Table 1. The overloaded and selected microgrids of the distribution network as well as their UPC and PDL in the considered study cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Overloaded Microgrid(s)</th>
<th>Selected Microgrids by the OMT</th>
<th>Self-sufficient Microgrids</th>
<th>P</th>
<th>UPC [pu]</th>
<th>CMG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>PDL [pu]</td>
<td>{MG-1, MG-2, MG-3, MG-4}</td>
<td>MG-1</td>
<td>MG-2</td>
<td>MG-3</td>
</tr>
<tr>
<td>Case-1</td>
<td>MG-3</td>
<td>0.60</td>
<td>{MG-1, MG-2}</td>
<td>{MG-1}</td>
<td>0.84</td>
<td>0.57</td>
</tr>
<tr>
<td>Case-2</td>
<td>MG-3</td>
<td>0.62</td>
<td>{MG-1, MG-2}</td>
<td>{MG-1, MG-2}</td>
<td>0.56</td>
<td>0.22</td>
</tr>
<tr>
<td>Case-3</td>
<td>MG-5</td>
<td>0.65</td>
<td>{MG-1, MG-2, MG-3, MG-4}</td>
<td>{MG-1, {MG-2}}</td>
<td>0.84</td>
<td>0.76</td>
</tr>
<tr>
<td>Case-4</td>
<td>MG-5</td>
<td>0.70</td>
<td>{MG-1, MG-2, MG-3, MG-4}</td>
<td>{MG-1, MG-2}</td>
<td>0.35</td>
<td>0.56</td>
</tr>
<tr>
<td>Case-5</td>
<td>MG-4, MG-5</td>
<td>0.35, 0.64</td>
<td>{MG-1, MG-2, MG-3}</td>
<td>{MG-1}</td>
<td>0.84</td>
<td>0.62</td>
</tr>
<tr>
<td>Case-6</td>
<td>MG-5, MG-6</td>
<td>0.65, 0.68</td>
<td>{MG-1, MG-2, MG-3, MG-4}</td>
<td>{MG-1, MG-2}</td>
<td>0.56</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Table-2. Time-sequence of the events in the considered study cases.

<table>
<thead>
<tr>
<th>t [s]</th>
<th>Case-1</th>
<th>Case-2</th>
<th>Case-3</th>
<th>Case-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Synchronization module sends an instant closing command to ISS of overloaded microgrid (MG-3).</td>
<td>Synchronization module sends an instant closing command to ISS of the first microgrid of selected two-microgrid combination (MG-1).</td>
<td>Synchronization module sends an instant closing command to ISS of overloaded microgrid (MG-5).</td>
<td>Synchronization module sends an instant closing command to ISS of the first microgrid of selected two-microgrid combination (MG-1).</td>
</tr>
<tr>
<td>0.1+</td>
<td>Synchronization module sends a synchronization command to ISS of self-sufficient microgrid (MG-1).</td>
<td>Synchronization module sends a synchronization command to ISS of the remaining microgrid of two-microgrid combination (MG-2).</td>
<td>Synchronization module sends a synchronization command to ISS of the self-sufficient microgrid with highest UPC (MG-1).</td>
<td>Synchronization module sends a synchronization command to ISS of the remaining microgrid of two-microgrid combination (MG-2).</td>
</tr>
<tr>
<td>0.95</td>
<td>ISS of MG-1 synchronizes with MG-3 and closes.</td>
<td>ISS of MG-2 synchronizes with MG-1 and closes.</td>
<td>ISS of MG-1 synchronizes with MG-5 and closes.</td>
<td>ISS of MG-2 synchronizes with MG-1 and closes.</td>
</tr>
<tr>
<td>0.95+</td>
<td>Synchronization module sends a synchronization command to ISS of the remaining selected microgrid (MG-2).</td>
<td>Synchronization module sends a synchronization command to ISS of the overloaded microgrid that can be supplied by this two-microgrid combination (MG-3).</td>
<td>Synchronization module sends a synchronization command to ISS of the remaining selected microgrids (MG-2, MG-3, MG-4).</td>
<td>Synchronization module sends a synchronization command to ISS of the remaining selected microgrids (MG-2, MG-3, MG-4).</td>
</tr>
<tr>
<td>1.54</td>
<td>ISS of MG-2 synchronizes with existing temporary CMG and closes. At this time, the desired CMG is formed.</td>
<td>ISS of MG-3 synchronizes with existing temporary CMG and closes. At this time, the desired CMG is formed.</td>
<td>ISS of MG-2 synchronizes with existing temporary CMG and closes.</td>
<td>ISS of MG-3 synchronizes with existing temporary CMG and closes.</td>
</tr>
<tr>
<td>2.46</td>
<td>ISS of MG-3 synchronizes with existing temporary CMG and closes.</td>
<td>ISS of MG-3 synchronizes with existing temporary CMG and closes.</td>
<td>ISS of MG-4 synchronizes with existing temporary CMG and closes. At this time, the desired CMG is formed.</td>
<td>ISS of MG-3 synchronizes with existing temporary CMG and closes.</td>
</tr>
<tr>
<td>3.88</td>
<td>ISS of MG-4 synchronizes with existing temporary CMG and closes. At this time, the desired CMG is formed.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.17</td>
<td>ISS of MG-2 synchronizes with MG-1 and closes.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.17+</td>
<td>Synchronization module sends a synchronization command to ISS of the overloaded microgrid that can be supplied by this two-microgrid combination (MG-5) and the remaining selected microgrids (MG-3 and MG-4).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.20</td>
<td>ISS of MG-3 synchronizes with existing temporary CMG and closes.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.22 ISS of MG-5 synchronizes with existing temporary CMG and closes.

12.21 ISS of MG-4 synchronizes with existing temporary CMG and closes. At this time, the desired CMG is formed.

<table>
<thead>
<tr>
<th>Case-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.1'</td>
</tr>
<tr>
<td>1.04</td>
</tr>
<tr>
<td>1.04'</td>
</tr>
<tr>
<td>1.38</td>
</tr>
<tr>
<td>1.38'</td>
</tr>
<tr>
<td>2.21</td>
</tr>
<tr>
<td>2.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.1'</td>
</tr>
<tr>
<td>2.06</td>
</tr>
<tr>
<td>2.06'</td>
</tr>
<tr>
<td>2.16</td>
</tr>
<tr>
<td>2.16'</td>
</tr>
<tr>
<td>2.25</td>
</tr>
<tr>
<td>2.26</td>
</tr>
<tr>
<td>2.27</td>
</tr>
</tbody>
</table>

$^t$ illustrates the time that the Synchronization module receives a closing confirmation signal, which is slightly higher than $t$ to reflect the communication delays.
Fig-1. a) Illustration of a distribution network consisting of multiple neighboring isolated microgrids, b) Schematic diagram of a distribution network composed of 3 isolated microgrids and their coupled combinations when MG-1 is overloaded, c) Flowchart of the process to interconnect neighboring microgrids, d) Developed local controller for the ISSes, e) Required communication links and the transferred data.
Fig. 1 continued.
Fig-2. Probable various interconnection topologies of neighboring microgrids: (a) Scheme-1, (b) Scheme-2: radial line, (c) Scheme-2: loop line, (d) Scheme-3, (e) Scheme-4.
Fig-3. Performance of the developed Synchronization module for various conditions: a) an overloaded microgrid with three self-sufficient microgrids, b) three overloaded microgrid(s) with four self-sufficient microgrids, c) an overloaded microgrid with a self-sufficient two-microgrid combination, d) an overloaded microgrid with a self-sufficient four-microgrid combination.
Fig-4. Simulation results of Case-1 to 6 illustrating the frequencies and status of the ISSes of the participating microgrids in a CMG.
Fig-A1. Per-phase representation of the considered normally-open ISSes among the neighboring microgrids.

Fig-B1. (a) Phase-a voltage at two sides of the ISS when the synchronization command is initiated, (b) Phase-a voltage at two sides of the ISS when two microgrids synchronize, (c) Difference of two instantaneous voltage waveforms shown in (b), (d) Current passing through the ISS.
Fig-B2. Required time for interconnection of microgrids for different $\Delta\theta$ and $\Delta f$. 

[Diagrams showing time vs. difference in angle and frequency]
Algorithm 1: Algorithm of the developed synchronization module

1. Fetch the selected microgrids from the OMT.
2. Call the number of overloaded microgrids as $K$.
3. Call the number of non-overloaded microgrids as $M$.
4. Define the self-sufficient microgrids and the relevant overloaded microgrids by comparing their UPCs and PDLs.
5. If there is at least one self-sufficient microgrid that can solely supply one or more overloaded microgrids then
6. Select the self-sufficient microgrid with the highest UPC and call this microgrid as MG-ss.
7. List the overloaded microgrids that MG-ss can supply solely within a temporary CMG under $P$.
8. Call the number of microgrids in $P$ as $R$.
9. Send an instantaneous closing command to the ISS of the first overloaded microgrid in $P$.
10. If the closing confirmation signal is received then
11. Send a synchronization command to the ISS of MG-ss.
12. If the closing confirmation signal is received then
13. End-if
14. Send a synchronization command to the ISS of other overloaded microgrids in $P$.
15. End-if
16. Send a synchronization command to the ISS of $M-1$ remaining non-overloaded selected microgrids,
17. $x = 1$
18. While $x \leq K-R$
19. If a closing confirmation signal is received from the ISS of a non-overloaded selected microgrid then
20. Define the microgrids coupled together based on the received closing confirmation signals and list them under $CMG$.
21. Define the un-coupled overloaded microgrids that can be supplied by the existing microgrids in $CMG$ and list them in $P$.
22. If a microgrid is listed under $P$ then
23. End-if
24. End-while
25. End-if
26. Else
27. $y = 1; \; j = 2; \; x = 1$
28. While $y \leq M-K$
29. $y = y + 1$
30. Define the self-sufficient $y$-microgrid combinations.
31. If there is at least one self-sufficient $y$-microgrid combination then
32. Select the self-sufficient $y$-microgrid combination with the highest UPC.
33. List these microgrids under $SS$.
34. List the overloaded microgrids that the microgrids of $SS$ can supply solely within a temporary CMG under $P$.
35. Call the number of microgrids in $P$ as $R$.
36. Send an instantaneous closing command to the $SS$ of the first microgrid of $SS$.
37. Send a synchronization command to the ISSes of all microgrids in the selected $y$-microgrid combination.
38. If $y$ closing confirmation signals are received then
39. Send a synchronization command to the ISSes of all microgrids in $P$.
40. Send a synchronization command to the ISS of $M-y$ remaining non-overloaded microgrids,
41. While $x \leq K-R$
42. If a closing confirmation signal is received from the ISS of a non-overloaded selected microgrid then
43. Define the microgrids coupled together based on the received closing confirmation signals and list them under $CMG$.
44. Define the un-coupled overloaded microgrids that can be supplied by the existing microgrids in $CMG$ and list them in $P$.
45. If a microgrid is listed under $P$ then
46. End-if
47. End-while
48. End-if
49. End-while
50. End-if
51. End-if
52. End-if
53. End-while
54. End-if
55. End-if