Measurement-Based Network Clustering for Active Distribution Systems

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Abstract—This paper presents a network clustering (NC) method for active distribution networks (ADNs). Following the outage of a section of an ADN, the method identifies and forms an optimum cluster of microgrids within the section. The optimum cluster is determined from a set of candidate microgrid clusters by estimating the following metrics: total power loss, voltage deviations, and minimum load shedding. To compute these metrics, equivalent circuits of the clusters are estimated using measured data provided by phasor measurement units (PMUs). Hence, the proposed NC method determines the optimum microgrid cluster without requiring information about the network's topology and its components. The proposed method is tested by simulating a study network in a real-time simulator coupled to physical PMUs and a prototype algorithm implementation, also executing in real time.

Index Terms—Active distribution system, network clustering, phasor measurement unit.

I. INTRODUCTION

THE PENETRATION of conventional and renewable distributed generators (DGs) is increasing in distribution systems. Due to the variable and intermittent behavior of DGs, ADNs are more dynamic and complex than conventional ones. Therefore, these systems need to meet new requirements in their protection, control and management system to guarantee their reliable, stable and safe operation. Smart grids have been introduced as a new concept that provides new capabilities to enhance the performance of distribution systems; the "self-healing" capability is one of them that may enhance the network reliability [1], [2]. To provide such self-healing capability, distribution systems should be equipped with software tools and devices capable of automatically handling the self-healing process when required [3].

A. Paper Motivation

During normal operation, active distribution networks are supplied through both transmission networks and DGs. However, following a fault, the entire (or a section of) distribution network may be disconnected from the main grid and the loads inside the on-outage section need to be supplied only by DGs. In this case, as a self-healing action, the on-outage section can be divided into a cluster of microgrids that operate individually to continue to reliably supply the maximum possible amount of loads [1].

Supply-adequacy is the primary requirement to fulfill by each microgrid; however, it is also possible to operate the on-outage section more effectively by dividing the section into a proper cluster of microgrids that meet a set of technical requirements.

B. Literature Review

In [3], distribution systems are divided into a cluster of microgrids through the allocation of distributed energy storage resources and distributed reactive sources. Thus, requiring the adding of various types of DGs and energy storage systems to the study grid to achieve the optimal clustering. In addition, the network clustering method presented in [4] includes means for optimum allocation of different types of DGs. Therefore, it can be considered as a method for the optimal distribution systems design. In fact, similar to the method presented in [3], using the method of [4] for an existing network requires to add various types of DGs to the grid. In [2], operation

of ADNs in form of several autonomous microgrid, named as multi-microgrid, was investigated. Indeed, multi-microgrid was introduced in [2] as a solution to enhance the reliability of ANDs in case of disturbances in the upstream network; then, the reliability aspects of the multi-microgrids were assessed. However, in [2] it is assumed that the borders of each microgrid are already determined and the operational conditions of distribution system, e.g., load profile and DG's available power, do not change the topology of multi-microgrid.

Furthermore, various parameters have been considered as the objective functions of the already presented NC methods. For example, the approach presented in [5] divides ADNs into a cluster of microgrids considering reliability and supply-adequacy indices; while, in the work presented in [6], the costs of communication links and economical aspects of the ADN are taken into account. In addition to above mentioned parameters, in [7], reliability indices and demand response transaction costs were also considered. The issues related to DG's operation were also considered in some works; for example, in [1], uncertainties related to DGs outputs and load consumptions has been taken into account to provide an optimal network clustering. Moreover, impact of the stability issues of the power electronics interface of DGs on the robustness of microgrid clustering were investigated in [8]. In [9] voltage and current controllability of multi-microgrid was studied and then a probabilistic index was defined to determine the controllability of multi-microgrids' voltages/currents. Based on the presented index in [9], the controllability of voltage and current are other factors that were considered in the network clustering method. However, in all of these methods, it is necessary to have sufficient and updated information about the network's topology and its components, which makes the methods vulnerable to changes in loads, the DGs' power, and network topology. Moreover, in these NC methods, it has been assumed that all the distribution feeders are equipped with Circuit Breakers (CBs) and consequently, each distribution line could be considered as a connection point to neighboring microgrids. However, this assumption is not valid for most of the existing distribution systems.

C. Paper Contribution

This paper presents a NC method that exploits a PMU-based equivalent circuit synthesis algorithm. The proposed method was implemented in a software prototype and is executed in a computer called in this paper as Central Management Unit (CMU). All measurement data from the PMUs are received by the CMU. In addition, each zone of the distribution network, bounded by the existing CBs, is equipped with a Zone Control Unit (ZCU) that is able to monitor DGs and to communicate with the CMU to disconnect loads when it is strictly necessary. Compared to previous works, the main contributions of the proposed method are summarized as follows:

1. In contrast to NC methods proposed in literature, the method proposed in this paper is measurement-based, i.e., it does not require the network's model (i.e., topology and equipment parameters). Using this approach,

the intermittent behavior of DGs (and their connection/disconnection), network reconfiguration actions and the addition of new feeders, do not impact the method's applicability and accuracy.

2. In previous works [1], [3]–[6], the borders within each microgrid cluster are determined assuming that there are switches installed at both ends of every distribution feeder. To relax this requirement in the proposed method, microgrid clusters are determined considering the location of the existing CBs. Hence, the method may be implemented in existing distribution systems without requiring additional CBs or switches at each line.

3. In order to operate the on-outage section optimally, the proposed NC method divides the on-outage section into a cluster of microgrids considering different factors, such as: minimizing total power loss, power quality issues, and DG characteristics. This is performed by computing several operational criteria using equivalent circuits estimated from PMU measurements. Note that the resulting microgrids may be reconfigured due to the real-time variations of loads, power of DGs, or any other changes in network elements that affect the operation of the on-outage section. Such variations are tracked by computing different quantitative metrics that after a significant change trigger alternative microgrid configurations that are recalculated to better satisfy the criteria.

4. The method has been implemented in a Real-Time Hardware-in-the-Loop (RT-HIL) test-bed that accommodates a real-time simulator to simulate an active distribution grid model, PMUs, and a real-time controller to implement the proposed NC method. Therefore, the issues related to the actual implementation of the method have been considered and assessed through experimental tests.

The rest of the paper is organized as follows. Section II explains the objective and constraints that are considered in the proposed NC method. The assumptions and steps of the proposed method are introduced in Section III, where the PMU-based equivalent circuit synthesis is also explained. Section IV introduces the study grid and the experimental setup, respectively. The experimental results are presented and explained in Section V. Conclusions are drawn in Section VI.

II. Operational Constraints and Requirements

This section explains the main concept, constraints and requirements of the proposed NC method. These will be used in Section III, where the steps of the proposed method are discussed in detail. It is worth noting that the term "zone", used throughout the paper, refers to any portion of the distribution network that can be separated from the rest by using existing CBs. A zone complies with the same measurement configuration conditions as a "cut-set" in [10].

A. Operational Constraints in Forming Microgrid Clusters

Supply-adequacy is the primary requirement for the isolated operation of each zone of the on-outage section. The criteria to

satisfy the supply-adequacy requirement are defined as the constraints explained in the sequel.

1) Load-Generation Balance: Load-generation balance is the most important constraint for autonomous microgrid operation. Each zone can operate as a microgrid if [11]:

$$\sum P_{S,i}(t) + \sum P_{W,i}(t) + \sum P_{PV,i}(t) \geq P_L(t) + P_{Loss}(t) \tag{1}$$

where $P_{S,i}$ $P_{W,i}$ and $P_{PV,i}$ are defined within the zone as the output power of the ith Dispatchable DG (DDG), the output power of the ith wind turbine and the output power of the ith PV unit, respectively. P_L and P_{Loss} are the total load and losses inside the zone. DDGs are basically DGs with controlled active power generation and voltage regulation capabilities and will be discussed further in criterion 3 of this section. Indeed, (1) determines the feasibility for the load-generation balance inside the zone (i.e., DGs power match the total load and losses).

In practice, the quantities in (1) may not be directly measured as voltage and current measurements are usually only available at substations, where CBs are installed. Therefore, the load/generation balance of the zone before becoming disconnected from the main grid can be determined by measuring the currents at its bounds [10]. Hence, the summation of the currents flowing through the borders of the zone can be calculated using (2), which will be used instead of (1) to evaluate the load/generation balance of the zone.

$$I_{DZ} = \sum_{i=1}^{N} I_{z,i}(t) \tag{2}$$

where I_{Zi} denotes the current at the ith connection point (border) of the zone, and I_{DZ} is the summation of the measured currents at the connection points. Note that currents flowing into and from the zone are assumed to be respectively positive and negative).

2) Generator Power Limits: Any generator has a stable operation if it works between its lowest and highest generation limits [12]. Therefore, the allowed generated power of a DG, considering its limits, can be defined as:

$$P_i^{min} \leq P_i(t) \leq P_i^{max} \tag{3}$$

where P_i^{min} and P_i^{max} are the lowest and the highest generation limits of the ith DG, respectively.

3) Generated Power of DDGs: DDGs are DGs, such as micro-turbines (MT) and diesel generators (DIG), that are capable of handling load variations and voltage regulation of the zone through appropriate controls. According to [5], the generated power of the DDGs should be at least 60% of their total load at the time of islanding. For this reason, a zone can be operated as a microgrid if:

$$\sum P_{S,i}(t) \geq 0.6 * P_L(t) \tag{4}$$

Each zone that satisfies the three conditions above for islanded operation, i.e., (2)–(4), is named a "fundamental microgrid" (FMG).

Note that the FMGs can either operate as islands or merge with each other to form a larger microgrid.

B. Considerations for Optimal Operation of the On-Outage Section

The criteria, mentioned in the previous section, determine the feasible FMGs. As FMGs can merge with each other in different combinations to form larger microgrids, there may be various possible configurations of the microgrid cluster through which the on-outage section can be operated. Therefore, further considerations are needed to select the optimum microgrid cluster that satisfies the following requirements.

Note that the requirements are assessed by computing additional metrics using the equivalent circuits of the zones that are obtained from the PMU data. This will be further explained in Section III.

1) Loss Minimization: The first factor considers the total power loss of the on-outage section for each possible configuration of the microgrid cluster:

$$F_{1,j} = \sum_{i=1}^{N_j} P_{Loss,i} \tag{5}$$

where $P_{Loss,i}$, $F_{1,j}$, and N_j are the power loss inside the ith microgrid, the total power loss of the jth possible microgrid cluster, and the number of the microgrids composing the jth cluster, respectively.

2) Voltage Deviations Minimization: The second factor determines the sum of voltage deviations at the boundary of all zones for each possible configuration of the microgrid cluster, as follows:

$$F_{2,j} = \sum_{k=1}^{N} |V_k - V_n| \tag{6}$$

where V_k, V_n, N, and $F_{2,j}$ are the voltage magnitude of the bus to which the kth CB within the on-outage section is connected, the nominal voltage, the number of CBs within the on-outage section, and the sum of absolute voltage deviations within the jth possible microgrid cluster. Observe that, as mentioned before, the CBs determine the boundaries of the zones; therefore, this factor is computed at the CBs' locations.

It is worth noting that, before computing $F_{2,j}$, all V_ks are checked against the grid bus voltage permissible range as shown in (7). Indeed, (7) that is a result of meeting the constraints in (1), is checked with the constraints that are assessed in Section II-A. The possible configurations of the microgrid cluster in which one or more V_ks violate the range are omitted from the list of candidate clusters.

$$V^{min} \leq V_k \leq V^{max}. \tag{7}$$

3) Load Shedding Minimization: The IEEE Std 1366-2012 presents several reliability indices to assess the operation of distribution systems [13]. Two of the most important and commonly used indices are the system average interruption frequency index (SAIFI) and the system average interruption duration index (SAIDI) [13]. According to the two reliability indices above, load shedding decreases the network reliability. Therefore, it is necessary to decrease the number and total power of the disconnected loads, while at the same time satisfying (1).
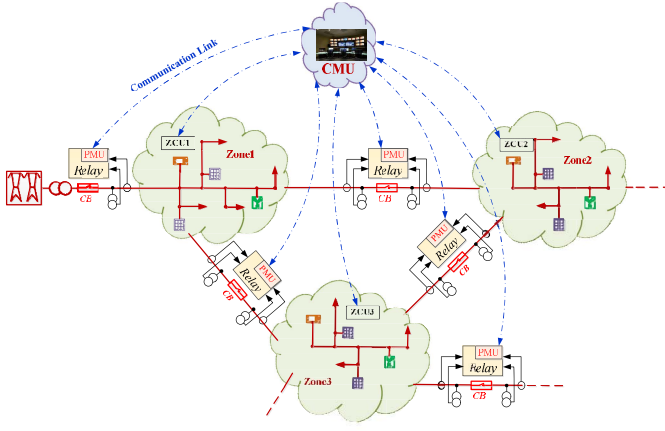
Fig. 1. Architecture required for the proposed NC method.

Fig. 2. Equivalent circuit of a typical zone bounded by n CBs [15].

Loads that have been shed to form FMGs can be re-connected if the FMGs that lost load are integrated to other FMGs with excess power capacity; thereby reducing the total disconnected load. Therefore, the third factor is defined in (8) is need to calculate the disconnected load for each possible network clustering configuration.

$$F_{3,j} = \sum_{i=1}^{N_j} P_{Dis,i} \qquad (8)$$

where $P_{Dis,i}$, $F_{3,j}$, and N_j are the disconnected power inside the ith microgrid, the total power shed in the jth possible microgrid cluster, and the number of the microgrids composing the jth cluster, respectively.

III. PROPOSED METHOD

A. Assumptions

The proposed method can be applied to large distribution networks under the following assumptions.

1) Grid Attributes: NC methods are typically used for large active distribution networks. These networks can be divided into multiple zones through the operation of CBs that are located throughout the network. Each zone may include different types of DGs, loads, and energy storage devices, and thus considered as a potential microgrid. In addition, it is assumed that each zone contains at least one DDG.

Note that the NC application executes immediately after the network is islanded (typically due to a fault occurrence) and when the on-outage section is in emergency condition. Therefore, the power generation of DDGs is adjusted without considering market aspects that are typically investigated in normal operating conditions.

2) NC Software and Hardware Architecture: Fig. 1 depicts the architecture required for the proposed NC method; it is built using a partially centralized and partially de-centralized methods. As the figure shows, each zone has an individual ZCU that monitors the zone's operational conditions; hence, the zone can be controlled using the de-centralized control logic. The available capacity of DGs inside the zone, the currents flowing through the boundaries (that are determined
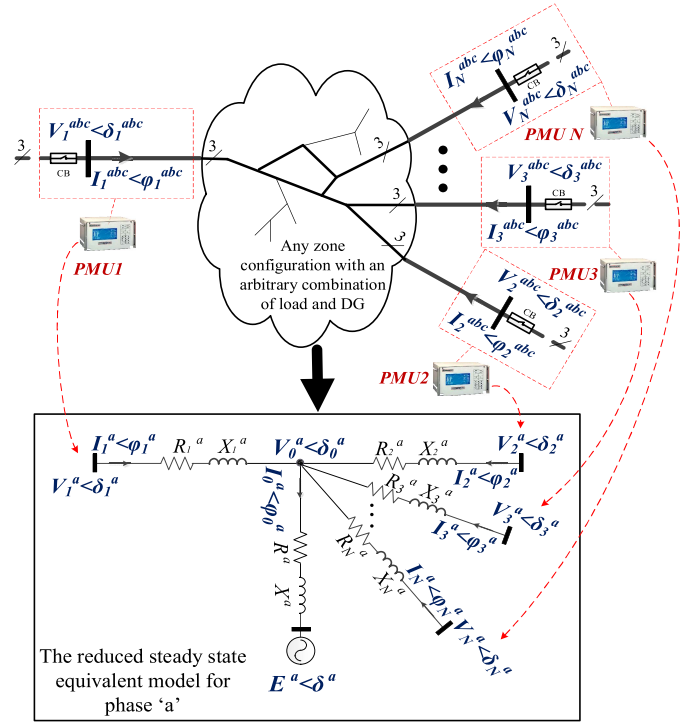
by CBs), and the status of CBs are all reported to the ZCU. Furthermore, the type of the DGs (dispatchable or not), and the load priorities are made available to the ZCU. When the zone is isolated, the ZCU sends the required power dispatch set-points to the DDGs to meet the loads' demand. Moreover, The ZCUs exchange necessary information (e.g., the total available power of DGs and CBs status) with the CMU through a communication network.

As mentioned before, the proposed NC method acquires PMU data to estimate the equivalent circuits of the zones. Therefore, PMUs are needed at CBs' locations to communicate the voltage and current synchrophasors with the equivalent circuit synthesis algorithm. It is worth noting that some of the currently available protection relays are equipped with synchrophasor functionalities [14], hence, they can operate both as a PMU and a relay. Therefore, the required synchrophasor measurements can be obtained by utilizing the PMU functionalities of the existing relays with no need to dedicated PMUs.

B. PMU-Based Equivalent Circuit Synthesis

As mentioned before, the proposed NC method makes use of a PMU-data-based equivalent circuit synthesis method, presented in [15] and assessed in a real feeder in [16], to evaluate the considerations and factors discussed in Section II-B. Provided that PMUs are installed at all CBs bounding the zones, each zone can be replaced by an equivalent circuit consisting of a voltage source and several R-L branches, as shown in Fig. 2. The number of branches is determined by the number of PMUs surrounding the zone (at least two PMUs are necessary).

As Fig. 2 shows, the equivalent circuit has at least three branches. In this equivalent circuit, it is assumed that the impedances of all the three main branches are the same (i.e., $R^i = R_1^i = R_2^i$ and $X^i = X_1^i = X_2^i$). Assuming that V_j^i and I_j^i are the voltage and current phasors of phase i measured by the jth PMU, the impedance of the main branches can be calculated as follows:

$$R^i + jX^i = \frac{V_1^i \angle \delta_1^i - V_2^i \angle \delta_2^i}{I_1^i \angle \varphi_1^i - I_2^i \angle \varphi_2^i} \quad (9)$$

where i denotes phases a, b, or c. Applying KVL along the first branch and the shunt branch yields (10) from which the voltage source phasor in the equivalent circuit can be calculated.

$$E^i \angle \delta^i = V_1^i \angle \delta_1^i - \left(R_1^i + jX_1^i\right)I_1^i \angle \varphi_1^i - \left(R^i + jX^i\right)\left(I_0^i \angle \varphi_0^i\right) \quad (10)$$

The impedances of the other branches are calculated by applying KVL on the corresponding loops as follows:

$$V_1^i \angle \delta_1^i - V_N^i \angle \delta_N^i = I_1^i \angle \varphi_1^i \left(R_1^i + jX_1^i\right) - I_N^i \angle \varphi_N^i \left(R_N^i + jX_N^i\right) \quad (11)$$

It is worth noting that the dimension of the admittance matrix of the estimated equivalent circuit is much smaller than the dimension of the Y_{Bus} matrix that would model the system in detail [17]. As a result, the forthcoming mathematical calculations used by the equivalent circuit require significantly less computing effort.

C. Steps of the Proposed Method

In this section, the steps of the proposed NC method are explained using the algorithm flowchart, shown in Fig. 3. As the flowchart shows, after the fault occurrence on a line, the method is applied to the on-outage section of the network according to the following steps.

Step 0 (Fault Location): After the fault occurrence and operation of the related CB(s), by making use of a fault locator algorithm, the CMU determines zones that are located inside the on-outage section and sends activation signals to the ZCUs of these zones. Moreover, it is assumed that a local load-shedding logic is used for each zone. In this case, according to the load priority, predetermined for ZCUs, load shedding is applied to the zones to satisfy constraints of (1) to (4).

Step 1 (Forming the FMGs): In this step, the constraints described by (1) to (4) are examined for each zone. The zones satisfying the constraints are considered as FMGs. However, it is clear that, in conventional distribution systems, these constraints cannot be met by all zones. Thus, the following actions are applied on these zones in order to convert them to FMGs:

1. If the initial necessary constraints are not satisfied by a zone, but sufficient generation and DDG capacity is available inside one of the neighboring zones, the feasibility to couple to the zone with excess power is investigated. If combining them satisfies the constraints of (1) to (4), the combination of the two zones is considered as an FMG. As a result, the FMG created in this stage includes more than one zone. Indeed, in this case, based on the saved pre-fault information (i.e., the
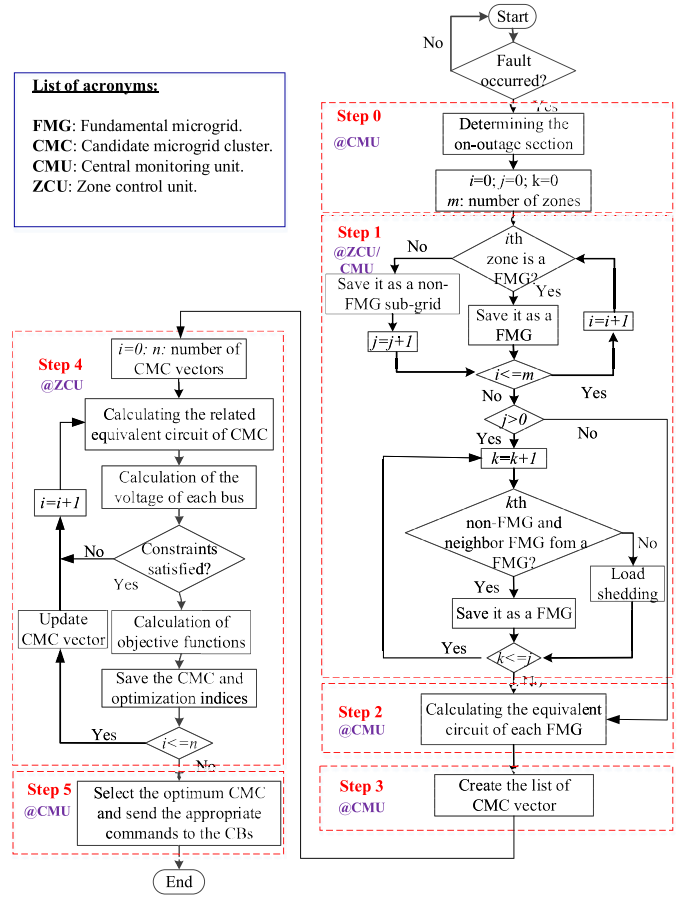

Fig. 3. The flowchart of the proposed NC method.

power of the connected loads, the output power and available capacity of DGs and the priority of loads), the CMU determines the borders of the FMGs and sends the amount of load which should be disconnected to the ZCUs. After that, the ZCU of each zone re-dispatch the DDGs and applies the required load shedding according to a local shedding priority list.

2. If coupling the zone with lack of power to its neighboring zones does not help satisfying (1) to (4), the zone is converted to an FMG by load shedding.

3. The output of Step 1 is basically a cluster of FMGs to secure reliable power supply for the maximum possible loads within the on-outage section.

Step 2 (Calculating the Equivalent Circuits of the Zones): The equivalent circuits of the zones, as described in Section III-B, are computed in this step. The CMU receives the required data, i.e., voltage and current synchrophasors, from the PMUs installed at the boundaries of the FMGs and calculates the equivalent circuit of each FMG. It is worth noting that, because the load-generation-balance of FMGs is controlled by DDGs, the generated power of DDGs may change during the network's isolation. Thus, this type of DGs is not included in the equivalent circuit, which necessitates installing PMUs at the connection points of DDG stations and the grid.

The PMUs streams the voltage and current synchrophasors to the CMU, where the equivalent circuits of the zones

are calculated. Hence, an overall equivalent circuit of the on-outage section is kept and updated in the CMU, and is used in Step 4 to determine the optimum clustering.

Step 3 (Determining the Candidate Microgrid Clusters): An FMG is the smallest portion of the on-outage section that can operate as an island considering constraints presented in (1) to (4). However, they can also merge with each other under various combinations to form larger microgrids. Hence, in this step, all possible combinations for FMGs' merging are determined, each resulting in a candidate microgrid cluster (CMC).

Each CMC can be identified by a $1 \times n$ vector containing the information on the status of CBs located between the FMGs. In this vector, 'n' denotes the number of CBs and the entries are '1' for the closed CBs and '0' for the open ones. For instance, the vector belonging to a CMC, containing three non-merged FMGs with two CBs between them, can be expressed as [0 0].

Consequently, in this step, the output of Step 3 is a set of CMCs, expressed by CMC vectors, is generated by the CMU in which each microgrid cluster can operate the on-outage section through microgrids that all satisfy the constraints for the autonomous operation, expressed in (1) to (4).

Step 4 (Computing the Factors Operational): In this step, the factors, presented in Section II-B are calculated for the set of CMCs, obtained in the previous step, using the equivalent circuits of the zones.

Furthermore, the possibility of re-connecting shed loads (in Step 1) is assessed for CMCs in which two or more FMGs are merged to form larger microgrids. To achieve this goal, the ZCUs of each CMC communicate together and re-dispatch the corresponding DDGs if they have available capacity.

Step 5 (Choosing the Optimum CMC): In the final step, the optimum CMC is determined out of the set of CMCs by computing a single objective function, F_m. This function is defined as the weighted sum of the factors computed in Step 4, which are weighted according to their priority and importance [18]:

$$F_m = K_1 \times F_1 + K_2 \times F_2 + K_3 \times F_3 \qquad (12)$$

where K_i is the weight of F_i and determines the importance of this factor. It should be noted that normalized values of F_1, F_2 and F_3 should be used in (12) as explained in [18]. In addition, the weight of each factor may vary from one network to another.

Using (12), the value of F_m is calculated for all CMCs, and the CMC that minimizes (12) is selected as the optimum cluster of microgrids. Finally, the CMU sends the appropriate command to the CBs locating between the FMGs to form the selected microgrids within the on-outage section.

D. Updating the Optimum Microgrid Cluster

It is notable that the clustering process should have a dynamic operation; thus, it is executed as often as needed to deal with the intermittent behavior of DGs. For example, assume that the predicted data of the output of the DGs in the next 2 hours are available in 30-minute time steps. This assumption imply that 1) the output of DGs is assumed to be constant during a 30 minute time frame, and 2) in each 30-minute the DG output for the next 2 hours is predicted. In this case, after each 30 minutes, it is necessary to investigate the initial conditions of the successful operation of each microgrid. If the microgrid does not satisfy the conditions presented in (1) to (4), the NC method should be executed again. To reduce the number of CBs operation, the optimization goals are not considered again provided that the conditions of (1) to (4) are satisfied. Also, the NC should be executed again after a large change in the loads.

IV. Hardware-in-the-Loop Real-Time Simulation Setup

A. Study Grid Model

The proposed NC method was applied to a 132-bus study grid that has been developed by extending the active distribution grid model presented in [19]. The grid also includes DC loads that are interfaced to the grid by use of AC/DC converters. The study grid is connected to the transmission system through a 132/36 kV substation where the CMU is located.

As shown in Fig. 4, the study grid consists of 8 zones, named as Zone1 to Zone8, each accommodating different types of single- and three-phase DGs and at least one DDG. The zones are separated by the CBs, named as CB1 to CB10. Note that in normal operation, all zones are connected to the main grid.

The protection relays, supervising the CBs, are of the type that can measure synchrophasors of voltage and currents; hence, these relays can operate as PMUs as well. Furthermore, each zone is equipped with a ZCU that monitors the zone's operational conditions and communicates with the CMU and related PMUs through the existing communication links.

B. Hardware-in-the-Loop Setup and Prototype Implementation

The proposed NC method has been evaluated by use of the RT-HIL testbed at SmarTS laboratory [20]. Fig. 5 shows the experimental setup used in this work. As the figure indicates, the study grid is simulated using the OPAL-RT eMegasim real-time simulator. Feeder voltages and currents are measured by relays' PMU type SEL-421 from Schweitzer Engineering Laboratories (SEL). The PMU data are then sent to SEL-5073 phasor data concentrator (PDC) that streams data over TCP/IP to a workstation computer holding the Smartgrid Synchrophasor Software Development ToolKit (S³DK) [21], which provides a real-time data mediator that parses the PDC data stream and makes it available to the user in the LabVIEW environment. The parsed PMU data is used for computation in Step 2. These computations, along with other information used for CMU computation, is sent to a Compact Reconfigurable IO systems (cRIO) from National Instruments (NI) Corporation where the remainder of the proposed NC method is implemented using LabVIEW programming tools. The output of the NC method, i.e., the vector of the optimum CMC, is sent back to the OPAL-RT simulator to form the selected microgrids within the on-outage section of the study grid. ZCUs are also modeled within the real-time simulator.
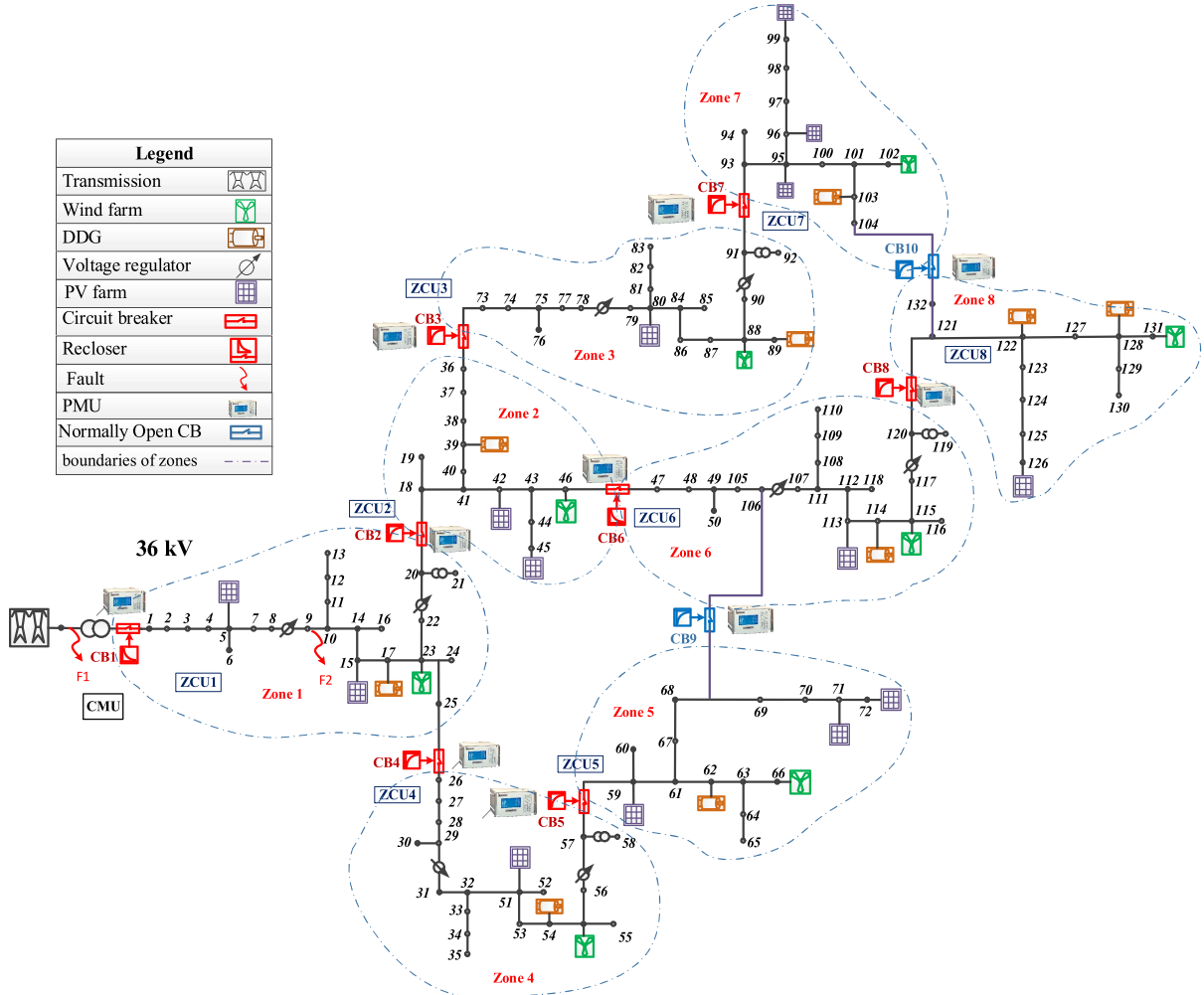
Fig. 4.   The study distribution grid.

V. Simulation and HIL Testing Results

A. Study Case 1; Fault Occurrence at Point F1

In the first section of the proposed NC evaluation, four various cases are considered after the fault occurrence at point F1 by use of the HIL setup introduced in Section IV-B. Following the fault occurrence at point F1 of Fig. 4, the distribution system becomes isolated from the transmission system.

In the following tests, it is assumed that the fault clearance time is one hour and half during which the generated power of non-dispatch-able DGs will remain constant (only the DDGs are re-dispatched). Moreover, the normally open CBs (CB9 and CB10) will remain open; thus, the status of these CBs is not reported in the CMC vectors. In other words, the status of CB9 and CB10 are considered in the NC method, but because it is assumed that the grid operator would like to keep them open, their status was not reported in the CMC vectors.

Table I shows the required information from all zones of the study grid that are reported to the CMU. Based on this information, it is clear that Zone6 cannot operate autonomously without a load-shedding process or connection

TABLE I
DATA REPORTED BY THE ZCUs TO CMU FOR STUDY CASE 1

Data from	Total connected load (kW)	Total DGs power (kW)	$\dfrac{P_{DDG}}{P_L}$	$\dfrac{P_{DDG}}{P_{DG}}$
ZCU1	2321	2630	0.65	0.57
ZCU2	1336	1570	1.12	0.96
ZCU3	1901	2520	0.79	0.60
ZCU4	1196	1530	1.25	0.98
ZCU5	1631	2680	0.92	0.56
ZCU6	1781	1600	0.84	0.94
ZCU7	1766	3240	0.85	0.46
ZCU8	2056	3200	0.73	0.47

to a neighboring zone. Therefore, the possibility of coupling Zone6 to Zone8 and also Zone6 to Zone2 are investigated in order to prevent the load-shedding in this zone.

As mentioned in Section III-C, the main multi-objective function (F) is determined based on the three basic factors whose weights are determined by the three coefficients ($K_1 - K_3$).
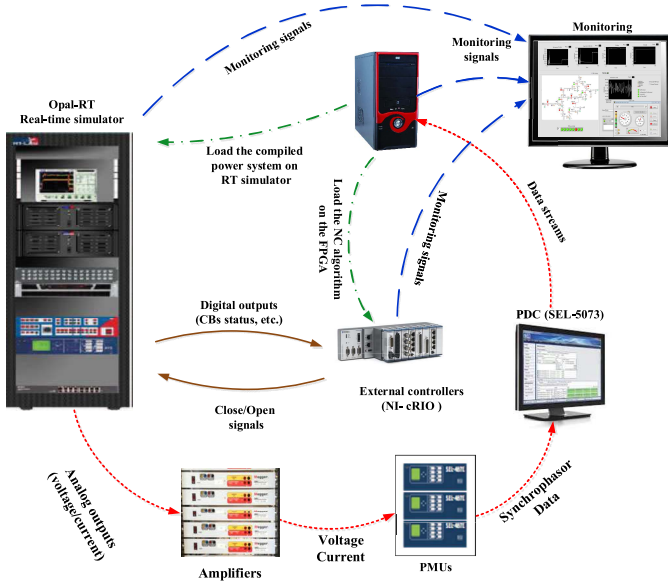
Fig. 5. The structure of the HIL test-bed used for the prototype implementation.

Fig. 6. Fundamental Microgrids and arrangement for CMC1.

TABLE II
THE OUTPUT OF THE NC METHOD CONSIDERING
DIFFERENT FACTORS

Case	K_1	K_2	K_3	output vector of the NC
A	1	0	0	[0 1 0 0 1 0 1 1]
B	0	1	0	[0 1 0 1 1 0 1 1]
C	0	0	1	Various arrangements e.g., [0 1 1 1 1 1 1 1]
D	1	1	1	[0 1 0 0 1 0 1 1]

TABLE III
OBJECTIVE FUNCTIONS FOR VARIOUS CMC CASES

	CB statuses	F_1	F_2	F_3	F_m
CMC1	[0 1 0 0 1 0 1 1]	**0**	**28.32**	**0**	**28.32**
CMC2	[0 0 1 1 1 0 1 1]	95.63	15.49	0	111.10
CMC3	[0 0 0 1 1 1 1 1]	58.44	25.32	0	83.76
CMC4	[0 1 1 0 1 0 1 1]	73.96	100	0	173.96
CMC5	[0 1 0 0 1 1 1 1]	0.58	52.92	0	53.50
CMC6	[0 1 0 1 1 0 1 1]	53.84	0	0	53.84
CMC7	[0 0 1 1 1 1 1 1]	100	42.24	0	142.24
CMC8	[0 1 0 1 1 1 1 1]	62.05	30.08	0	92.13
CMC9	[0 1 1 1 1 0 1 1]	95.22	20.97	0	116.19
CMC10	[0 1 1 1 1 1 1 1]	99.48	48.02	0	147.50

In this section, four different cases with different values for K_i are considered. For each case, the optimum microgrid cluster is obtained using the proposed NC method. These cases are:

A. Clustering based on the first factor metric presented in (5)
B. Clustering based on the second factor presented in (6)
C. Clustering based on the third factor presented in (7)
D. Clustering considering all the factors presented in (5)-(7)

The output of these cases are reported in Table II in which the effects of each factor is defined by a coefficient (i.e., K_i). This table illustrates that considering different factors results in different optimum microgrid clusters. Therefore, as a crucial stage of the proposed NC method, it is necessary to determine appropriate values for the coefficients in (12).

For example, Table III, shows that for the main factor, F_m, when the values of coefficients are: $K_1 = 1$, $K_2 = 1$, and $K_3 = 1$, the output vector of the proposed NC determines that CB2, CB5, CB7, and CB8 should remain closed and the other CBs should open. Moreover, the output vector of this case determines that the optimum operational condition is achieved by clustering the study grid into four microgrids (MG1 consists of Zone1 and Zone2; MG2 consists of Zone4 and Zone5; MG3 consists of Zone6 and Zone8; MG4 consists of Zone3 and Zone7).
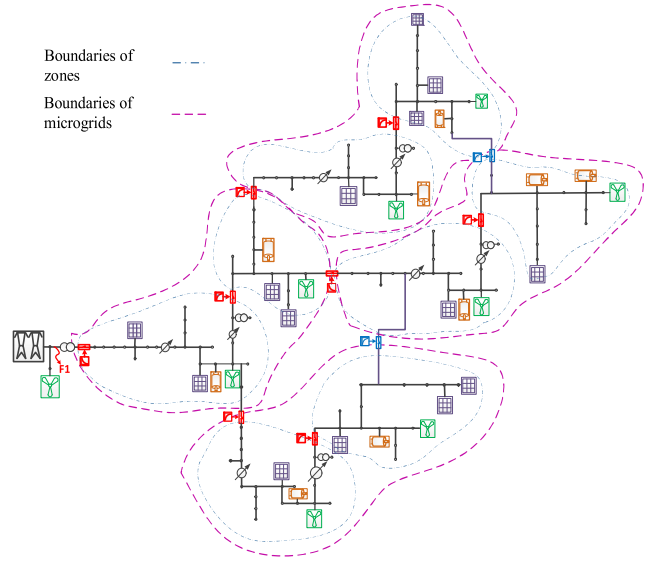
The normalized values of the factors (i.e., *F1*, *F2*, and *F3*) for some of the possible CMCs, corresponding with case D of Table II, are reported in Table III. The table shows that CMC1 and CMC5 can provide the minimum power losses for the study grid; while, the minimum voltage deviation is achieved when either CMC6 or CMC2 is selected. Furthermore, this table shows that, CMC10, which is the case that all the zones of the on-outage section remain connected together, leads to the largest power loss. In addition, because the study grid is equipped with enough DGs, all of the reported CMCs can provide the load-generation balance and hence, the load shedding is not necessary. Finally, as mentioned above, CMC1 is the best possible option to cluster the study grid. Fig. 6 shows the network clusters when the trip signals are sent to CBs according to CMC1.

The simulation results also show that compared to CMC10 (where all zones are connected), CMC1 provides improvements of 5.6% and 4.5% on total voltage deviation and total power loss, respectively.

TABLE IV
DATA REPORTED BY THE ZCUs TO CMU FOR STUDY CASE 2

Data from	Total connected load (kW)	Total DGs power (kW)	$\dfrac{P_{DDG}}{P_L}$	$\dfrac{P_{DDG}}{P_{DG}}$
ZCU1	After the fault occurrence, disconnects from the grid.			
ZCU2	1336	1500	1.12	1
ZCU3	1901	1270	0.26	0.39
ZCU4	1196	1030	0.83	0.97
ZCU5	1631	1760	0.62	0.58
ZCU6	1781	1600	0.84	0.94
ZCU7	1766	1890	0.57	0.52
ZCU8	2056	1850	0.46	0.51

TABLE V
FMGs AFTER LOAD-SHEDDING FOR STUDY CASE 2

FMG	Zones	Disconnected load (kW)
FMG1	Zone5, Zone6	0
FMG2	Zone2	0
FMG3	Zone3	1067.67
FMG4	Zone4	166
FMG5	Zone7	99.33
FMG6	Zone8	472.67

B. Study Case 2; Fault Occurrence at Point F2

In the study of the previous section, it was not necessary to apply the load-shedding process to the FMGs. In this section, this study aims to show the NC method's performance when DGs, located inside the isolated grid, cannot supply all the connected loads. In this case, assume that after the fault occurrence at point F2, breakers CB1, CB2 and CB4 are opened to isolate the faulted zone (Zone1). After that, the proposed NC method is applied on the rest of the grid. It is also assumed that normally open CBs (i.e., CB9 and CB10) could be closed or opened according to the output of the NC method. Note that results of this study case are obtained from the off-line simulation.

Table IV shows information reported by ZCUs to the CMU; this table indicates that only Zone2 and Zone5 can operate as autonomous FMGs and the other zones cannot operate autonomously without a load-shedding process or connection to a neighboring zone. As it is shown in the flowchart of Fig. 3, the autonomous FMGs are determined in the Step 1 of the proposed NC method. Applying Step 1, the FMGs and the amount of disconnected loads of each FMG are determined as it can be found in Table V. Table V shows that Zone5 and Zone6 are connected together and create a FMG without load-shedding; however, the other FMGs are formed by applying a load-shedding process. The rest of the NC process is similar to Study Case 1.

Assume that the values of coefficients in (12) are selected as: $K_1 = 0.5$, $K_2 = 0.75$, and $K_3 = 1$. It is noted that, the selected values for K_i coefficients of this study case minimize the amount of disconnected load as first priority. Accordingly,

the output vector of the proposed NC method is obtained as: [0 0 1 0 1 0 0 0 1 1] which determines that CB3, CB5, CB9, and CB10 should be closed and the other CBs are opened.

VI. CONCLUSION

This paper proposed a measurement-based NC method for ADNs. In this method, after a fault occurrence, the on-outage section is divided into a cluster of autonomous microgrids to guarantee the reliable operation of the microgrids cluster with minimum power loss and voltage deviation. Compared to the already available NC methods, the proposed method determines the optimum microgrid cluster without requiring any information about network's topology and equipment parameters. The HIL simulation results confirmed that the propose NC method determines the best possible arrangement for the microgrids.

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