Graph-Theoretic Partitioning for Differential Zone Protection in an Islanded Microgrid

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***Abstract*—The deployment of microgrids improves the reliability and resiliency of the electric power grid. Microgrids mitigate the impact of power outages. Microgrids, on the other hand, introduce new challenges to the power system. Microgrid protection is a technological issue that arises in microgrid design and operation. These challenges arise due to the distinction between microgrids and conventional electrical grids. Differential protection is fast, selective, and sensitive; it provides a potential solution to microgrid protection. The differential zone protection scheme is a cost-effective variation of differential protection that improves system reliability while decreasing the cost of the protection scheme. To deploy a differential zone protection scheme, it is necessary to divide the network into distinct protection zones. The number of protective zones results in a different level of microgrid system reliability. This paper presents a graph partitioning approach for differential zone protection. Using the algorithm, the microgrid is partitioned into a number of protection zones. The proposed protection method is validated using the IEEE-13 node system as a microgrid.**

***Index Terms*—Micrigrid, Microgrid Protection, Differential Protection, Graph Theory, Graph Partitioning Algorithm**

I. Introduction

A microgrid is a power network with distributed energy resources (DERs) and loads [1]–[3]. A microgrid connects loads and DERs with clearly defined boundaries and supports both grid-connected and islanded operation modes. Energy security, economic benefits, and clean energy integration are driving microgrid development and implementation in areas with existing electrical grid infrastructure [3]. Its potential to improve reliability and resiliency of the electric power grid is a primary motivation. Microgrids can supply critical facilities and communities when the major grid is down due to weather or other catastrophic events [4]. Prevalent microgrid issues include technical, regulatory, financial, and stakeholder challenges [3]. Microgrids have technological, dual-mode, power quality, and protection challenges [3], [5]. This paper discusses microgrid protection issues and solutions.

Microgrids require protection in order to de-energize and isolate faults before they cause harm to people or facilities. Protection systems keep important infrastructure functioning by isolating the faulted component(s) or system(s) [6]. Traditional distribution systems are designed and operated with a single source and a radial topology of the feeder. Microgrids, on the other hand, may be fed from a variety of distributed sources, altering the direction and magnitude of fault current. Microgrid protection is a critical concern in an islanded operation mode [7]–[10]. The fault currents in a grid-connected and an islanded microgrid differ due to the significant penetration of inverter-based resources. IBRs can generate fault currents that are difficult to detect or isolate using a conventional protection scheme. Microgrid protection issues arise when a microgrid contains a large number of DERs. Additionally, the penetration of IBRs complicates microgrid protection by introducing new issues, such as limited fault current contributions. Additionally, the modes of operation raise unique issues, such as variable fault current levels in each mode. The following are some primary protection challenges that arise in microgrid protection [7]–[10]:

- Bidirectional flow of current.
- Variable fault current level.
- Limited fault current produced by IBRs.
- Protection blinding.

Some protection schemes for microgrids have been proposed recently [8], [11]. The literature classifies these protection schemes according to their fundamental concepts. Microgrid protection systems are divided broadly into four categories: adaptive, differential, traveling wave, and others [12]. Differential protection is utilized for microgrid protection. Current differential protection is unaffected by variations in the fault current, bidirectional current flow, state of DERs, or changes in system configuration [12]. A number of differential protection systems have been proposed [13], [14]. The differential protection schemes are fast, selective, and sensitive; however, the protective approach can be costly.

E. Sortomme et al. [15] proposed a cost-effective differential zone protection scheme. This approach divides the microgrid into smaller protective zones. In each zone, the sum of all entering and exiting currents should be zero. For each zone, the differential current is defined as the sum of all incoming and outgoing currents. The protection zones are determined by a genetic algorithm that attempts to

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minimize the cost of the protection devices and the cost of customer interruption over a ten-year period. In this design, each protective zone is assumed to have a balanced generation and load.

This paper introduces a graph-based partitioning technique for determining the protection zones in a differential zone protection scheme. The microgrid will be divided into distinct protective zones using a graph partitioning algorithm [16]. This graph partitioning algorithm optimizes the generation-to-load ratio in each protection zone. As a result, the proposed protection scheme PPS ensures an acceptable generation load balance in each protection zone. During a fault, the affected zone will be isolated; the remaining zones will operate as a single large zone with adequate generation load balance.

The remaining of this paper is organized as follows. Section II presents the PPS. Section III summarizes the simulation results with the PPS. Finally the conclusion and suggested future work are in Section IV.

II. The Proposed Protection Scheme

A. Differential Zone Protection Scheme

The differential zone protection scheme is an effective way to protect microgrids. Microgrids can be divided into "islands" (protection zones), each with its own independent protection system. The protection scheme proposed in this paper is a differential zone protection that employs a new methodology for determining the optimal number of protection zones. The protective zones should have an adequate generation load balance. The differential zone protection scheme necessitates the installation of a protective relay at each network source and load. The load relays could be replaced by smart current sensors capable of measuring current phasors. The reason for replacing load relays with smart current sensors is that current interruption at the load is not essential to isolate the network. The relay located at each source end will prohibit the source from supplying power to the network.

B. Graph Partitioning

Graph partitioning techniques have been used for applications in electric power systems. In [17], [18], the electrical network is reconfigured following significant disturbances using graph partitioning approaches. The implementation of the differential zone protection scheme requires the electrical network to be divided into small protection zones. The graph partitioning approach is an effective method to divide an electric network. Li et al. [17] developed a graph partitioning algorithm for splitting the electric grid into K islands while the generation load imbalance is minimized. The electric network is transformed into a graph G using this approach; the network nodes serve as the vertices V of the graph, while the lines connecting the nodes serve as the graph's edges E. This graph is an undirected edge-weighted graph, each of the edge-weight a_{uv} being the absolute value of the real power flow on the line.

C. Proposed Protection Scheme

In this paper, the graph partitioning algorithm in [17] is utilized to divide the microgrid into small protection zones. The segmentation of the microgrid takes place in stages. Divide the microgrid into two zones as a first stage. Zones A and B will be designated as the protection zones. The second stage is to determine whether the two split zones, A and B, may be further divided into more zones. The condition for dividing zones is that they have more than one generation source. Each resulting zone should be capable of functioning independently of the main microgrid.

Zone feasibility depends on the microgrid's topology and how unbalanced loads are distributed. The load on distribution networks is frequently unbalanced. Microgrids are also often used in distribution networks. The graph partitioning algorithm will keep splitting the microgrid until it achieves the unreliable condition of each DER having its own zone. To terminate the partitioning process, several constraints are necessary.

The microgrid is divided into small zones using graph partitioning. There might be a significant imbalance in these zones, or they could have only single-phase or two-phase networks. It is assumed that the DERs are three-phase. As a result of this circumstance, three-phase DERs may be used to serve a zone with only single-phase or two-phase power demands, which is not desirable. As a result, when this condition is fulfilled, the graph partitioning process will come to an end. On the other hand, to prevent the partitioned zones from overloading, the power transfer between the partitioned zones should not exceed 10% of the combined load of the two zones. Then, the partitioning process will be terminated, and the new zones will be rejected. In summary, every zone is considered feasible to be partitioned if the following requirements are met:

- Each zone should have an adequate load balance between generation and load.
- Each zone contains three-phase power demand.
- The power transfer between the partitioned zones should not exceed 10% of the combined load of the two zones.

The partitioning procedure is depicted in Figure 1. After partitioning the microgrid, each zone will be protected by the differential zone protection scheme separately. The total number of protective devices that will be used in this protection scheme is as follows:

- The number of digital relays utilized will be equal to the sum of the number of generation sources and the number of created protection zones.
- The number of the smart current sensors will be equal to the total number of loads.

On the other hand, obtaining current phasor measurements from various locations throughout the network and comparing them during the same time frame is required by the PPS. Differential protection is intended to be instan-

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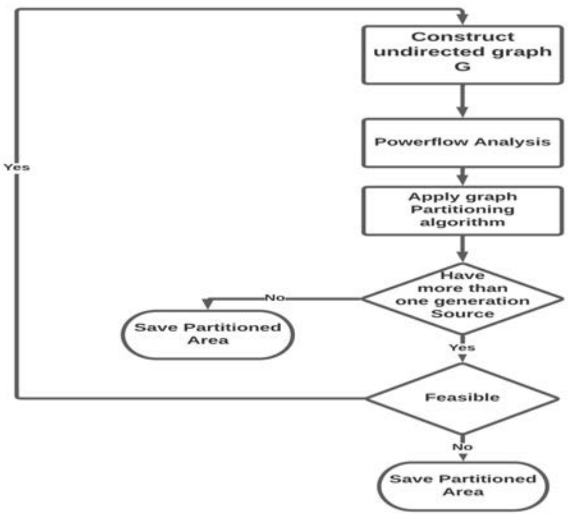

Fig. 1: The Partitioning Process

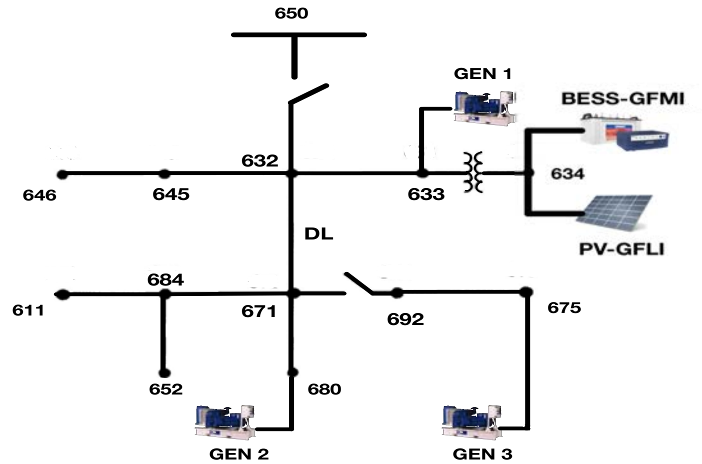

Fig. 2: The IEEE-13 node microgrid.

taneous. Thus, the electric network should be equipped with rapid standard-based communication capabilities. In this paper, it is assumed that the communication link exists and functions as in previous differential protection schemes [15].

III. Simulation

A. Applying the PPS to the IEEE 13-node microgrid

Microgrids are often connected to distribution networks. The IEEE 13-node test feeder provides a good test case for the PPS. By adding a generation source and main connecting switch, this test feeder is viewed as a microgrid. The main connecting switch is installed between node 650 and node 632. This switch determines whether the microgrid operates in a grid-connected or an islanded mode. This paper is concerned with microgrids that operate in an islanded mode; hence, all simulations assume that the main connecting switch is open.

The microgrid is equipped with three synchronous generators. These generators, which are located at nodes 633, 675, and 680, have a total capacity of 1375 kVA, 2187.5 kVA, and 1375 kVA, respectively. These generators are equipped with the SEXS automatic voltage regulators (AVR) and a DEGOV1 governor speed control with a droop of 5%. Also, this microgrid is equipped with two inverter-based resources (IBRs). These IBRs are a grid following photovoltaic (PV-GFLI) and a droop control grid-forming battery energy storage system (BESS-GFMI) with a droop of 1%. These IBRs are installed on node 634 with a capacity of 500 KVA for the PV-GFLI and a capacity of 125 KVA for the BESS-GFMI. The IEEE-13 node microgrid is depicted in Figure 2.

The microgrid is separated into two protected zones by the PPS. The first protective zone contains nodes 634, 633, 632, 645, and 646, as well as the distributed load DL. The first zone is equipped with a single synchronous generator and two IBRS with a capacity of 2000 kVA , a total load capacity of 1000 kW and 663 kVAR. On the other hand, the second protective zone encompasses nodes 675, 692, 671, 680, 684, 652, and 611. The second zone is equipped with two synchronous generators totaling 3562.5 kVA, a total load capacity of 2466 kW and 739 kVAR.

To implement the PPS, six digital relays are needed. Each DERs node will be equipped with a digital relay to monitor the current entering the zones, and node 671 will include a single relay between zones 1 and 2. In comparison, the required number of smart current sensors is equal to the number of loads. Thus, nine smart current sensors are required, assuming that distributed loads require just one sensor. Table I summarizes the PPS for the IEEE 13-node microgrid.

TABLE I: Summary of the PPS for the IEEE 13-node microgrid.

	Zone 1	Zone 2
Nodes	634, 633, 632, 645, 646, DL	675, 692, 671, 680 ,684, 652, 611
Generation sources	1	2
Installed capacity	2000 kVA	3562.5 kVA
Load consumption	1000 kW	2466 kW
Digital relays	6	
Smart current sensors	9	

After implementing the PPS, a power flow study was performed. Zone 1 supplies zone 2 with about 221 kw through node 671, according to the power flow results. The power transfer between the two zones is roughly 6.3%of the microgrid's total load.

B. Validation of PPS

Two scenarios are simulated to validate the protection system. In the first scenario, at t = 100 s, a three-phase-to-ground fault occurs in zone 1 between nodes 633 and 632. This scenario is used to demonstrate the protection system's response to a fault in zone 1. During the fault, the differential current in zone 1 should have significant values, whereas the differential current in zone 2 should be unaffected. The second scenario is identical to the

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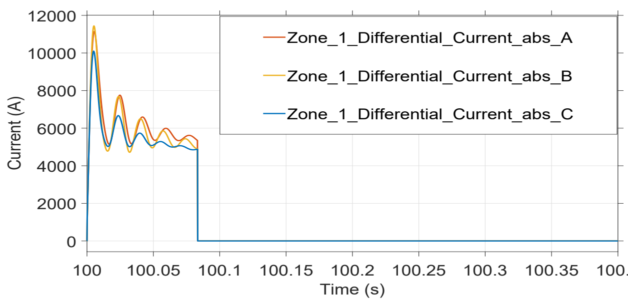
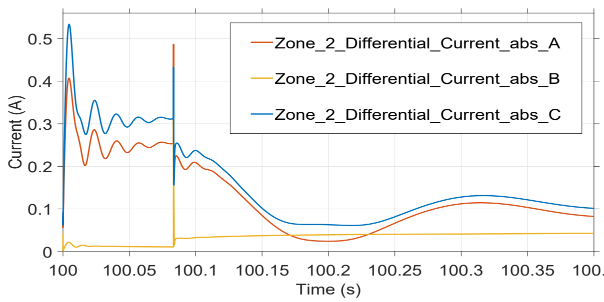
first, except that the location of the fault in zone 2 lies between nodes 675 and 692. The first simulation scenario is depicted in Figure 3. The differential currents in zones 1 and 2 are depicted in Figure 3a and 3b, respectively. The differential current in zone 1 is high, but the differential current in zone 2 is negligible.

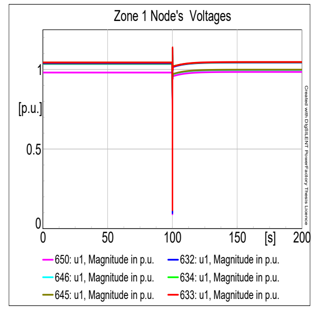


(a) Zone's 1 differential current magnitudes.

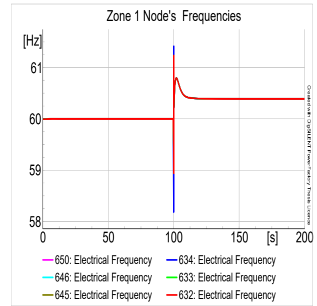


(b) Zone's 2 differential current magnitudes.

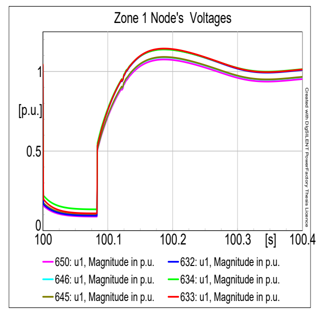
Fig. 3: Protection zone's differential current magnitudes during fault in zone 1.



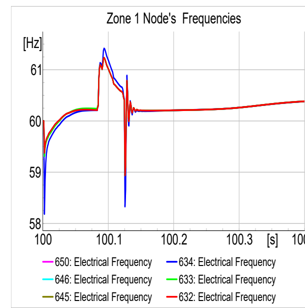
(a) Zone's 1 node voltages.



(b) Zone's 1 node frequencies.



(c) Transient response of zone 1 nodes voltages.



(d) Transient response of zone 1 nodes frequencies.

Fig. 4: Zone 1 nodes voltages and frequencies.

C. Impact on Microgrids

The DigSilent Powerfactory software is used to simulate the PPS's influence on the microgrid. The PPS is applied to the IEEE-13 node microgrid shown in figure 2.

In the second scenario, the impact of a three-phase-to-ground fault in zone 2 is simulated. The simulation lasts for 200 seconds, with the fault occurring at time t = 100 s and then zone 2 is isolated and all the DERs in zone 2 is tripped after five cycles. Figure 4 shows the voltages and frequencies of zone 1 nodes. Zone 1 nodes voltages are shown in Figure 4a. Figure 4b illustrates the zone 1 nodes frequencies. Zone 2 has been isolated, while Zone 1 is operational and has experienced a loss of load. The transient response for both zone 1 node voltages and frequencies are depicted in Figures 4c and 4d, respectively. Additionally, the frequency of zone 1 nodes fluctuated between 58 Hz and 61.5 Hz for a short duration, then settled at 60.39 Hz because zone 1 was supplying power to zone 2. In contrast, after the fault is cleared, the voltages on zone 1 nodes return to normal. The IEEE 13-node microgrid simulation indicates that the PPS has a negligible impact on the system. Because the PPS is based on the graph partitioning algorithm with minimized generation load imbalance in each zone, the separation of the microgrid protection zones transition occurs smoothly after clearing the fault. The microgrid continues to supply the remaining zone with an acceptable transient response. (An alternative approach is to shut down all zones upon the occurrence of a fault. Then the zones isolated from the fault can be recovered following a restoration process. This approach would be safer but there will be a short outage in all zones.) The increasing penetration of inverter-based resources (IBRs) in microgrids creates significant control issues, particularly for islanded microgrids. While the PPS works well in an IEEE 13-node microgrid with a low IBR penetration, it has challenges in microgrids with a high IBR penetration or microgrids that are totally powered by IBRs.

D. Applying the PPS to large microgrid

The IEEE 13-node microgrid is a small system. The benefits of the PPS will become apparent with larger system. A differential zone protection scheme was applied to an 18-node distribution microgeid [15]. Implementing the PPS into that system will result in dividing the microgrid into four protection zones as shown in Figure 5.

The PPS requires the installation of 33 digital relays and 22 smart current sensors. All the protection zones will have sufficient capacity except for zone 1. The installed capacity in zones 1, 2, 3, and 4 is 664 kW, 864 kW, 564 kW, and 964 kW, whereas the total load consumption is 791 kW,

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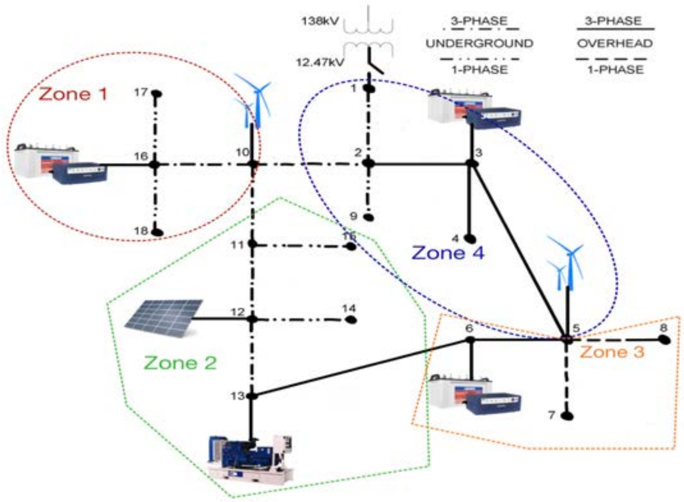

Fig. 5: The 18 node microgrid protection zones.

512 kW, 374 kW, and 956 kW, respectively. However, in the event of any fault occurring in the microgrid, only the affected zone will be isolated, while the remaining zones will operate as one large zone with adequate capacity.

IV. Conclusion and Future Works

Protection is crucial for microgrids. This paper proposed a graph-based theoritic partitioning for differential zone protection in both islanded and grid-connected modes of a microgrid. This scheme's protective zones are carefully determined using a graph partitioning algorithm to provide a proper balance between generation and load. To avoid overloading the remaining zones, when a fault occurs in a microgrid, only the faulty zone is isolated.

An IEEE 13-node microgrid is used to examine the PPS's ability to detect and isolate the affected zones in the event of a fault. This same microgrid's impact is also modelled using Digsilent Powerfactory software. The results show that the PPS works well with microgrids with low IBR penetration. Moreover, the separation of the microgrid protection zones transition occurs smoothly after isolation.

However, while that protection scheme achieves its goal, it has limitations and practical drawbacks. The proposed scheme's graph partitioning is dependent on the power flow results. The generation load balance may be disrupted if the power flow results change due to DERs installation or removal. Furthermore, differential protection is communication-dependent and, therefore, communication failures can impact differential protection. Due to this protection scheme's high reliance on the power flow, it needs to be modified to ensure generation-load balance if any of the DERs are de-energized, or in the case of networked microgrids. A microgrid update may requires a reconfiguration of the protection zones. A microgrid cyber-physical model is necessary to validate the communication system's impact on the power system.

The increasing penetration of inverter-based resources (IBRs) in microgrids creates significant control issues, particularly for islanded microgrids. While the PPS works well in an IEEE 13-node microgrid with a low IBR penetration, it has challenges in microgrids with a high IBR penetration or microgrids that are totally powered by IBRs. Thus, To ensure that this protection scheme works in microgrids with high IBR penetration, the microgrid control system should be investigated and improved.

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