Real-Time Dynamic Protection Zone Determination for Interconnected Power Systems using Network Theory Principles

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SUMMARY

As power systems become even more complex and dynamic as a result of interconnections, deregulation and the proliferation of Distributed Energy Resources (DERs), Centralized Protection and Control (CPC) has been proposed as an effective means of providing adaptive, sensitive, reliable, and effective protection. Such CPC approaches are designed to simultaneously protect multiple segments of an interconnected power systems such as networked microgrids.

However, the structure and connections in interconnected power systems are based on the dynamic behaviours in power markets which are often determined by the supply and demand interactions among the market participants. Also, the intermittent nature of DERs make their connections dynamic as well. Furthermore, interconnected power systems integrated with DERs or operating as networked microgrids can be operated in the grid or islanded modes, which cause their topologies to constantly change. Thus, the protection zones in such power system scenarios are dynamic and cannot be determined *a priori*. This paper presents a new network theory-based approach capable of real-time dynamic protection zone determination in interconnected power systems or networked microgrids using wide area information from switching devices and equipment status. The proposed approach is tested using a microgrid network for various topology scenarios. Results obtained are promising and demonstrate the effectiveness of the proposed approach to adapt to the changing topology of networked power systems.

KEYWORDS

Adjacency matrix, centralized protection, graph theory, microgrids, protective relaying, RTDS, zone selection.

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INTRODUCTION

Microgrids are parts of the power system with distributed generation or renewable energy resources, loads, energy storage, and Energy Management System (EMS) within an electrical boundary [1]. Microgrids in close geographical proximity can be interconnected together to form 'networked microgrids'. Networked microgrids are collectively seen by the utility as a single, aggregated, and controllable entity [13]. A cluster of networked microgrids can be owned by a utility or by other entities. When owned by other entities, they can either be operated by the utility or by a third party [1]. The interconnection of these microgrids can be a serial connection between multiple microgrids to the utility via a single feeder, or the connection of parallel microgrids to the utility using a single feeder. Microgrids can also be interconnected to the utility using multiple feeders. Some of the benefits of networked microgrids are improvements in their efficiency, reliability, sustainability, security, resilience, and economics [2].

The dynamic nature of interconnected power systems and microgrids where DERs and loads are constantly added coupled with the interaction between energy markets implies that their topologies will constantly change. This would also result in a constantly changing protection zones.

Zone selection has always played an important role in bus protective relays. Buses serve as the point of common connection for generation, transmission, and load circuits in traditional power systems and in microgrids. Typically, all the circuits connected at a bus must be tripped for bus faults using bus protective relaying. The status of the disconnectors at each terminals are commonly used by bus protective relays to determine the appropriate current signals to assign to the differential protection elements. A zone selection method for multi-bus protection using graph theory was proposed in [3]. In [4], a bus differential relay was applied together with a directional relay for multi-bus protection.

Centralized protective relaying is similar to multi-bus protection since multiple power apparatuses need to be protected. Generally, pre-determined (static) protection zones in wide area protection and control schemes will result in protection coordination problems especially in overcurrent protection, intertripping schemes or permissive protection schemes where protection systems rely on the receipt of signals from other devices before they can operate. Thus, new approaches for real-time determination of the protection zones in interconnected and networked microgrids need to be explored. To the best of our knowledge, there are no existing literature on zone selection techniques for interconnected/networked microgrids protection. The remainder of the paper is structured as follows. Section II presents the proposed protection zone determination algorithm, while Section III describes the experimental setup, real-time implementation, and the results obtained. Section IV summarizes the contribution of the paper.

PROPOSED PROTECTION ZONE DETERMINATION METHOD

A centralized protection is a high-performance computing platform with protection, control, automation, monitoring, and asset management functionalities [5]. A zone determination method suitable for centralized protection in interconnected power systems using wide area measurements of CB and switch statuses is explored in this paper. The proposed approach models interconnected power systems as network graphs, and it comprises of a system-wide topology processor and a zone determination algorithm. Further details are provided in the proceeding subsections.

Topology processor

The prevailing topology of a given power system can be determined from a network graph created using an adjacency matrix constructed from the information obtained from circuit breaker and switch statuses at the nodes and equipment in the power system.

Graph theory is a major branch of combinatorial mathematics and has been extensively applied in various fields [6]. Networked microgrids with n nodes can be modelled by a graph $G\{V, E\}$ using an a $n \times n$ adjacency matrix A. Vertices $V = \{v_0, v_1, \ldots, v_n\}$ is a non-empty finite set of elements, and the edges $E = \{(v_0, v_1), \ldots, (v_i, v_j), \ldots, (v_m, v_n)\}$ is a finite set of unordered elements. An edge e_{ij} is a pair of vertices (v_i, v_j), v_i and v_j are referred to as adjacent or neighboring vertices. $A = \{a_{ij}\}$, and the element $a_{ij} = 1$ if the nodes i and j are linked by an edge, while $a_{ij} = 0$ if otherwise. Table I presents the descriptions used in this paper to show the relationship between the power system components and the graph components.

Table 1: Electrical components and equivalent graph elements

Graph elements	Electrical component
Vertices	Busbars, nodes, terminals
Edges	Circuit Breakers (CBs), disconnecting switches, CT branches, CB-CT branches, power transformers

The above can further be illustrated using a section of the IEEE-13 node distribution system [7] shown in Figure 1. Table 1 gives the vertices and edges in the feeder. The open or closed condition (status) of the edge components are used in constructing the adjacency matrix of the feeder. The corresponding network graph representing the prevailing power system topology is created from this adjacency matrix. The feeder in Figure 1 can be represented by a network graph with 6 vertices and 5 edges (Figure 2). If the breaker on Line 650-632 is tripped open by a protective relay due to fault or by an operator for maintenance, the adjacency matrix and the graph structure would automatically update based on the edge statuses received. The update would result in the removal of edge E1 from the edge list. Thus, the matrix elements corresponding to E1 changes from 1's to 0's as highlighted in Figure 3. In practical systems, the currents from such feeders become zero and are no longer available for protection algorithms. Thus, the protection zone will change.
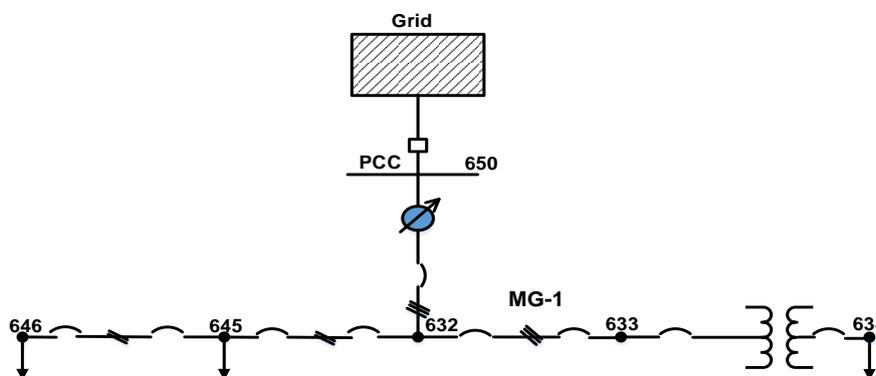

Figure 1 – A section of the IEEE-13 node distribution system

Table 2: Graph components for the study section

Graph component	Substation component
Vertices	Bus 650, Node 632, Node 633, Node 634, Node 645, Node 646
Edges	E1, E2, E3, E4, E5

```
0  1  0  0  0  0
1  0  1  0  1  0
0  1  0  1  0  0
0  0  1  0  0  0
0  1  0  0  0  1
0  0  0  0  1  0
```
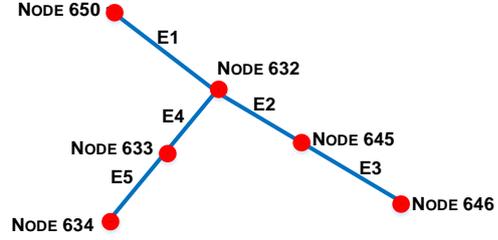
Figure 2 – Example-network graph for steady-state condition (a) Adjacency matrix, (b) network graph

```
0  0  0  0  0  0
0  0  1  0  1  0
0  1  0  1  0  0
0  0  1  0  0  0
0  1  0  0  0  1
0  0  0  0  1  0
```
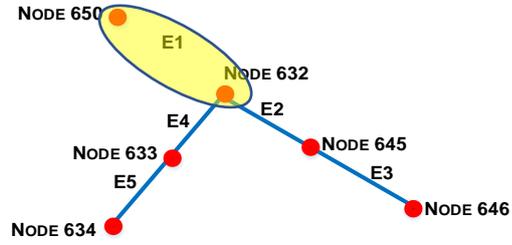
Figure 3 – Example-network graph for CB1 open scenario (a) Adjacency matrix, (b) network graph

Zone Selection Algorithm

Some graph theory terminologies [8] are applied in this paper in the determination of the protection zones in an interconnected power system or networked microgrids. These terminologies are defined as follows:

Definition 1: A subgraph $H\{V(P), E(P)\}$ is the graph induced by a subset of vertices V with degree $d(v) > d_{thr}$ in each of the interconnected system or networked microgrids.

$$V(P) = \{x_0, x_1, \ldots, x_r\} \tag{1}$$
$$E(P) = \{(x_0, x_1), (x_1, x_2), \ldots, (x_{r-1}, x_r)\} \tag{2}$$

Such that $V(P) \in V$, $E(P) \in E$, $H \in G$, and x_0, x_r are end vertices. The subgraphs are obtained for vertices with degree $d(v) > d_{thr}$, where d_{thr} is a user-defined threshold ($d_{thr} = 3$ was used in this paper).

Definition 2: The degree of a vertex is the summation of the number of edges connected to that vertex

Definition 3: Hubs are vertices with a high degree value, and represents the central vertex connecting all the other vertices.

Definition 4: The shortest path d_{ij} (distance) between vertices i and j is the path with the fewest number of links.

Definition 5: The diameter d_{max} is the maximum shortest path in the network. The diameter between the end nodes and the subgraph with the highest centrality is found. Table 2 summarizes the above-mentioned definitions.

Table 2: Description of the graph components

Graph Component	Description
Network graph	Networked microgrids (MGs)
Subnetworks	Individual MGs
Subgraphs (Z_B)	Vertices with degree $d(v) > d_{thr}$.
Shortest path (Z_F)	Path between subgraphs
MG Diameter (Z_{EH})	Path between end vertices in the MGs and hubs

A flowchart of the proposed zone determination method is shown in Figure 4. The topology processor receives and tracks the changes in the statuses of the Fault Interruption Devices (FIDs), and applies network theory in the construction of the adjacent matrix equivalent to the prevailing system topology and the creation of the graph network. The term 'FIDs' is broadly used in this paper to include CBs, disconnectors, and switches. The zone selection algorithm applies the methodology presented in the definitions in its simplest form by creating subgraphs, shortest paths between end nodes and hubs, and the paths between hubs. The Z_B zones correspond to bus zones made up of at least one incoming feeder and a minimum of two outgoing feeders. This would typically require a bus differential protective relay or a differential protection algorithm implemented on a centralized protection platform. Also, the Z_F zones represent feeders, and requires an overcurrent protective relay or the deployment of an appropriate protective algorithm on a centralized protection platform. Furthermore, the Z_{EH} zones correspond to major branches connecting two bus zones. These are typically protected using line differential protective relays. It is assumed that transformers and DERs have dedicated unit protection. All these graph components form the protection zones in the interconnected systems and are updated automatically using their FID statuses. It should be noted that $d_{thr} = 2$ may be used depending on the extent of the protective coverage required.
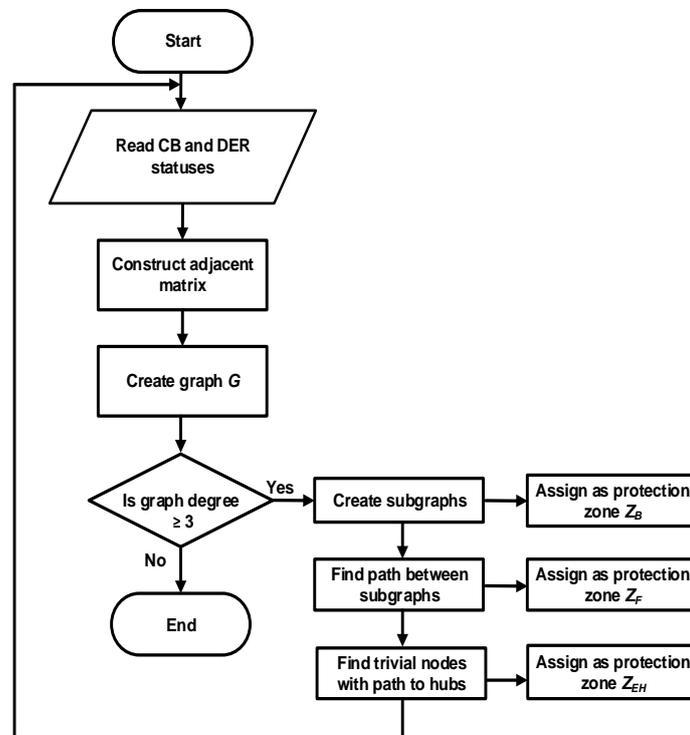

Figure 4 – Proposed protection zone determination method

EXPERIMENTAL SETUP AND REAL-TIME IMPLEMENTATION

Study Network

The proposed zone determination method is tested using the IEEE 13-node distribution feeder [7] shown in Figure 5. This is a heavily loaded 4.16 kV, 60 Hz unbalanced feeder with a total load of 3.4 MW. The feeder comprises of three phase, two phase, and single phase overhead lines and underground cables, and was partitioned into 3 interconnected microgrids (MG-1 to MG-3) by integrating DERs at the load points DERs at Nodes-634, -671, and 675. The DERs are sized to be able to supply the entire loads in the MGs when operating in the islanded mode.
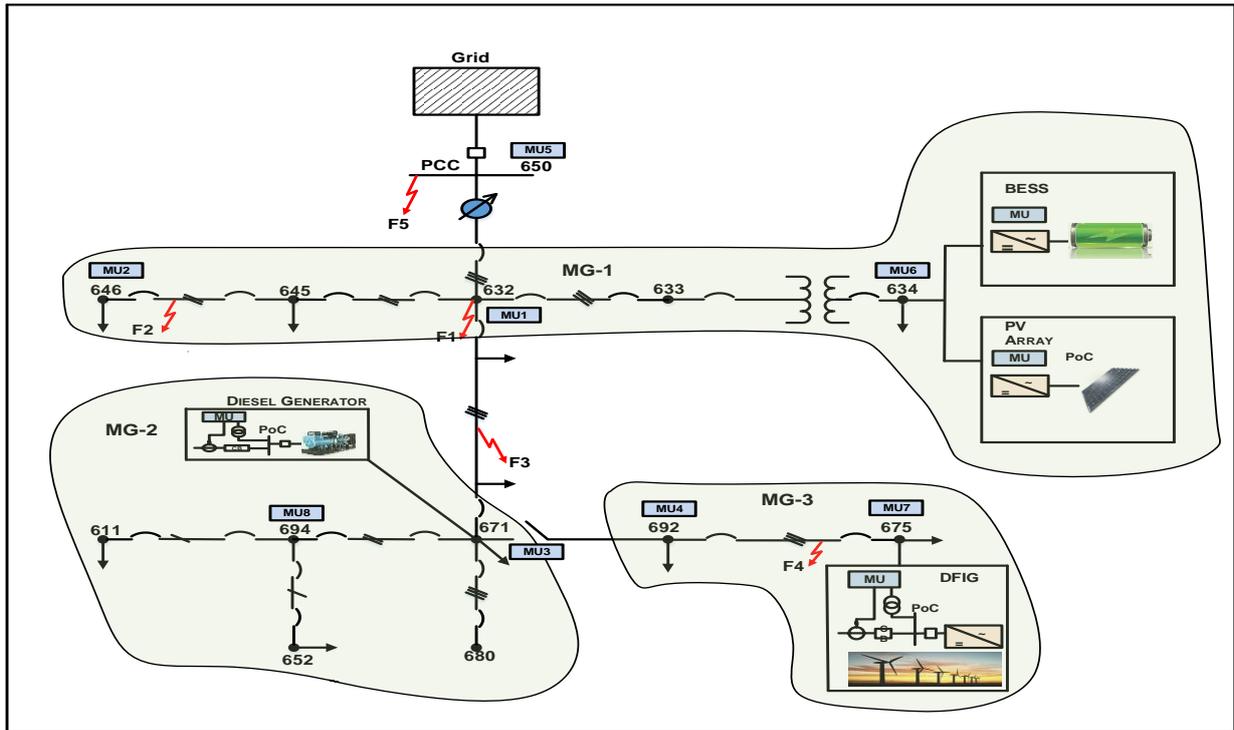

Figure 5 – Modified IEEE13 node distribution test system

Proof-of-Concept Lab-Scale Real-Time Testbed

The proposed zone determination method was implemented in MATLAB. The statuses of the FIDs in RSCAD are published in real-time from the Real-Time Digital Simulator (RTDS®) to MATLAB via the GTNET-SKT card using socket communication protocol.

The GTNET-SKT served as the socket server, while MATLAB was the socket client. The communication is via TCP communication protocol. Typically, the client initiates the communication, and the server starts to send the data to the client once the socket communication is established. MATLAB receives the incoming packets and extracts the data points containing the statuses of the FIDs. Afterwards, the processing of the topology and the zone selection algorithm are executed and the results of these functions are sent as zone enable bits to the RTDS in order to activate the protection zones.

Figure 6 – The implemented proof-of-concept real-time testbed

Experimental Results

The adjacency matrix and the graph topology at steady-state condition is shown in Figure 7, while Figure 8 gives the updated adjacency matrix and network graph for a fault condition on line 671-684 resulting in the opening of the FID at Node-671. From Figure 8, it can be seen that the highlighted entries in the columns corresponding to edge 671-684, change from ones to zeros. This also changes the protection zones as the edge (Z_{EH} zone) between Node-671 and Node-684 no longer exists. The adjacency matrix for a more complicated scenario in which the CBs at Nodes-633, -645, -646, PV and BESS are opened is shown in Figure 9. Table 3 gives the protection zones obtained for the above-mentioned scenarios. The initial number of protection zones in the steady-state was 13, while the number of protection zones for the second and third scenarios is 10 each. However, the electrical elements in the Z_{EH} zones in the second and third scenarios are different.
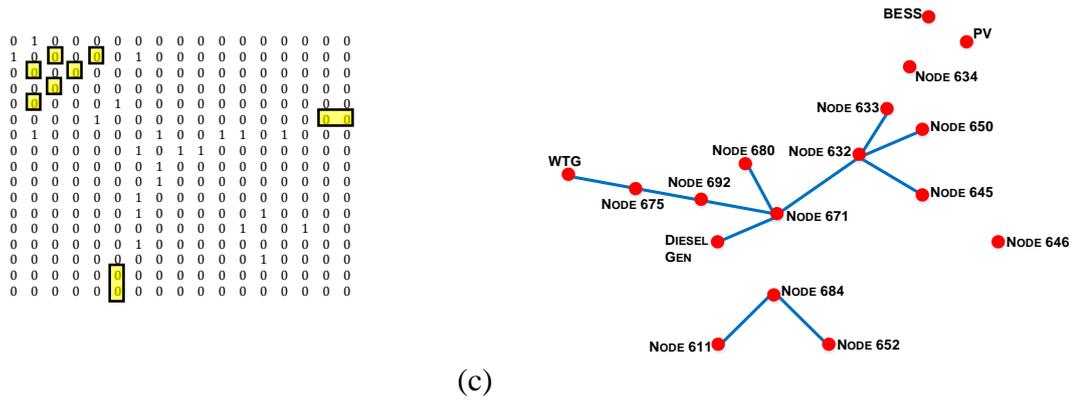

(a)

(b)

(c)

Figure 7 – Adjacency matrices and graphs for (a) steady state condition, (b) open CB at Line 671-684 (c) open CBs at Line 645-646, line 633-, PV, and BESS

Table 3: Protection zones for case studies 1-3

Case study	Scenario	Number of Prot. zones	Protection zones
Case study-1	Steady-state (All CBs closed)	13	Z_B:{632,671,645,633},{671,680,684,692}, {684,611,671,652} Z_{EH}: {632-671}, {684-671} Z_F: {All end nodes-to-nearest hub}
Case study-2	Node-671 CB open	10	Z_B:{632,671,645,633},{671,680,684,692}, {684,611,652} Z_{EH}: {632-671} Z_F: {All end nodes-to-nearest hub}
Case study-3	Node-633, 645, 646, PV, BESS CBs open	10	Z_B:{632,671,645,633},{671,680,684,692}, {684,611,671,652} Z_{EH}: {632-671} Z_F: {All end nodes-to-nearest hub}

From the foregoing, it can be seen that having pre-determined (static) protection zones and fixed electrical elements per zone will result in protection coordination problems especially for intertripping and permissive protection schemes since no permissive or blocking signal (key) will be sent from a disconnected zone.

CONCLUSION

This paper presented a new method for real-time dynamic protection zone selection suitable for interconnected or networked microgrids with dynamic/constantly changing topology. Tests for various topology scenarios were carried out using a lab-scale real-time testbed comprising of the RTDS, GTNET card, and MATLAB. The communication of the switching information from the RTDS to MATLAB was via socket programming via the GTNET card. Several tests for various operating scenarios and grid topology was investigated. The results obtained demonstrated the ability of the proposed method to adapt to topology changes in interconnected or networked power systems.

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