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Graph Algorithms for Quick Fault Detection in Reconfigurable Microgrid

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Abstract: Microgrids are the future of growing consumer power demand. The addition of renewable energy Resources to microgrid makes the power flow to be bidirectional. Reconfiguration of the microgrids occurs due to RES, load and utility grid connection and disconnection. Thus, conventional protection strategies are inapplicable to microgrids and are a challenge for the protection engineers to clear the fault. This study proposes Fredman-Tarjan's algorithm for identifying the current topology of the microgrid. The Dijikstra and Floyd-Warshall path recovery algorithm are also used to identify the shortest path from a fault to the nearest operating source. The algorithm ensures that during the process of fault clearance, minimum part of the network is disconnected from the healthy portion of network. The proposed algorithm is tested and validated on a 16-bus microgrid network and an IEEE 69-bus distribution network.

Key words: Fredman-Tarjan algorithm, Dijkstra's algorithm, Floyd-Warshall algorithm, microgrid protection, distribution, India

INTRODUCTION

Microgrid is a combination of Distributed Generators (DG) and loads in addition to a main power grid (Swathika and Hemamalini, 2016a, b). They have two different modes of operation: grid connected mode and islanded mode (Swathika *et al*., 2016). In grid connected mode, utility grid feeds the load demand of the distribution network. In case of a fault in the utility grid, the microgrid switches itself into islanded mode where the DGs in the distribution network handle the load requirements. The DGs are connected or disconnected from the utility grid depending upon the varying load demand. These are the prominent reasons that trigger the reconfiguration of microgrid and this makes the topology of microgrid dynamic. The inapplicability of conventional protection schemes in microgrid and bidirectional power flow adds up to the complexity of the protection engineering.

The microgrid uses a central protection system to monitor the status of DGs, loads and the utility grid. Communication assisted protection strategies are a common solution to the protection of microgrid (Swathika and Hemamalini, 2016, 2017; Laaksonen *et al*., 2014; Che *et al*., 2014; Nikolaidis *et al*., 2016).

Common issues like sympathetic tripping, false tripping, blind zone, variation in fault levels and unwanted islanding are the result of distributed generations Swathika and Hemamalini, 2015).

For the identification of shortest path in the microgrid, a graph theory based algorithm is employed Swathika *et al*., 2015a, b). This study proposes Dijkstra or Floyd-Warshall algorithm along with Fredman-Tarjan algorithm for the protection of reconfigurable microgrids. These algorithms identify the current topology of the network. Whenever, a fault occurs in the network, they identify the shortest path to isolate it. This scheme ensures that minimum consumer loads are disconnected while protecting the microgrid.

For the protection of microgrid following points must be taken into consideration (Swathika *et al*., 2015a, b; Swathika and Hemamalini, 2015; Zayandehroodi *et al*., 2012). Both external and internal fault identification is feasible given that the fault current level is low. If a fault happens in the utility grid, the consumer load demands are met by the DGs and microgrid is said to be in islanded mode. If there is a fault in the microgrid, the utility side consumers are unaffected. To meet the power supply demand continuously, backup protection arrangement is done for both grid connected mode and the islanded mode.

Shortest path identification problem: The objective is to minimize the number of loads disconnected by identifying the shortest path from the operating source and the faulted point:

$$\min d = \min (P) \quad (1)$$

Where:
- d = Distance between faulted point to point of common coupling
- P = Paths that exist between faulted point to point of common coupling

This is subjected to the constraint that, the shortest path identified from the network using the proposed

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algorithm should be a radial network. The proposed set of algorithms is heuristic and is based on non-mathematical rules.

MATERIALS AND METHODS

Fredman-Tarjan is a concept based on graph theory to analyse and produce a minimum spanning tree. The objective of this algorithm is to achieve a path that has the sum of weights of all the edges in the tree as minimum. The algorithm reduces the running time of Dijkstra's shortest path algorithm from:

$$O(m\log_{(m/n+2)}n) \text{ to } O(n\log(n+m))$$

Where:
n = Number of vertices
m = Number of edges connecting the vertices

Similar to the tree concepts in data structures, the Fredman-Tarjan algorithm uses Fibonacci heaps or the idea of packets. It groups the edges into packets and handles only one edge per packet to the main algorithm. When the algorithm processes that edge then the next edge in the packet is considered.

Consider a system having 'x' members such that all connected nodes are functional. If at any certain instance only first 'q' nodes are functional, then we develop a network using only these active nodes. These active nodes form a web with each other directly or indirectly for communication between them.

The study discusses how Fredman-Tarjan algorithm is used along with Dijkstra and Floyd-Warshall algorithm to identify the shortest path for traversal with minimum time complexity. The Fredman-Tarjan algorithm stores the number of active nodes in the system, generating their graph network. This network is further fed into the Dijkstra and Floyd-Warshall path recovery algorithm to produce sequence of traversal through the network considering low cost and efficient path for operation.

For an electrical grid, Loads (L) Utility Grid (UG) DG sources and the common Point of Coupling (PCC) are assumed to be the active nodes. Also, we assume the edge weight as '1'. If 'N' is the number of active nodes in the network, then a dimension matrix of size N×N is built. For a node connected or disconnected, the shortest distance is updated accordingly.

For our problem, we consider the utility grid as our base node and for any alterations in the grid, the change is directed to and from the base node. For the problem, the following properties must hold true.

For all vertices a, b∈V, 'x' can be considered as the shortest path for traversal from a to b using its weight function w, only if it holds true for w^ as well. Where w^(a, b) = w(a, b)+Dist[a]-Dist[b].

Algorithm 1; Dijkstra's algorithm:

Step 1: Initialize variables for 'Number of nodes[int n]', 'The node to be visited[int v]' and 'The number of paths[int p]

Step 2: Initialize the weight matrix C[ ][ ] using 2 dimensional array. C[i][j] is the cost of going from vertex i to vertex j

Step 3: Enter the path matrix which is also a 2 dimensional array and the number of rows is equal to the number of paths and number of columns is equal to the number of nodes

```
Step 4: for (i = 1; i≤p; i++)
  { distance[i] = 0
    Row = 1
  { for (j =1; j≤n; j++)
      If(row is not equal to V)
      Column = path[i][j+1]
       Distance [i] = distance[i]+cost[row][column]
  }
  Row = column
  }
```

Step 5: Initialize index 'i' for comparison to get the shortest path
Step 6: The shortest path will be displayed on the output screen

For all edges (a, b) the new calculated weights must be non-negative. Dijkstra's algorithm can be employed in both undirected and directed graphs considering that all edges must have non-negative weights and the graphs must be connected. The Dijkstra's algorithm maybe used to find the shortest path with a time complexity of O (nlog(n+m)).

Whereas, the Floyd-Warshall's path recovery algorithm when employed, finds the shortest path of all the paths in a weighted graph with positive or negative edges but no negative cycles. The algorithm takes $O(n^3)$ time complexity and $O(n^3)$ space.

Algorithm 2; Floyd-Warshall algorithm:

Step 1: A graph is considered G(V, E, W), where 'V' is number of vertices (nodes), 'E' is number of edges and 'W' weight of the edge

Step 2: Give the number of vertices as first input and adjacency matrix graph [ ][ ] as second input:

- graph[i][j] should be zero if i = j
- graph[i][j] should be "infinity" if edge (i, j) does not
- otherwise, graph[i][j] is the weight of the edge (i, j)

```
Step 3:  Void Floyd Warshall()
           { for( int k = 0; k<n; k++ )
for( int i = 0; i < n; i++ )
for( int j = 0; j < n; j++ )
graph[i][j] = min( graph[i][j], graph[i][k] + graph[k][j] )}
```

Step 4: Now graph[i][j] is the length of the shortest path distance from i to j

Step 5: For extracting the final shortest path:
Initialize a path matrix path [ ][ ], it stores the last vertex visited on the path from i to j
Path[i][j] = i if (i! = j) and there exists an edge from i to j and NULL otherwise

```
•  for( int k = 0; k<n; k++ )
   for( int i = 0; i<n; i++ )
   for( int j = 0; j<n; j++ )
   if (graph[i][k]+graph[k][j]<graph[i][j])
{  graph[i][j] = graph[i][k]+graph[k][j]
   path[i][j] = path[k][j];}
Return p
```

Step 6: Thus, we get the shortest path and shortest distance

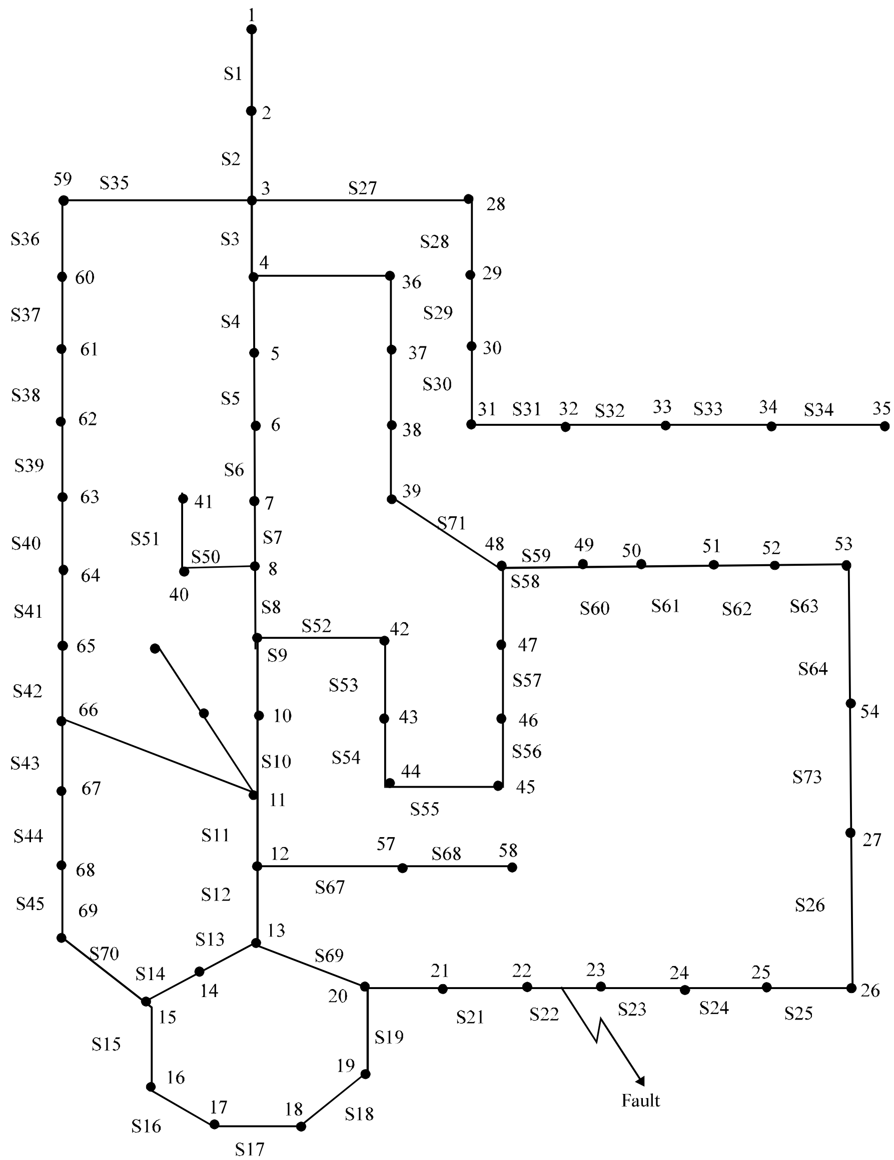

Fig. 1: IEEE 69 bus distribution network

RESULTS AND DISCUSSION

Simulation results: The IEEE standard 69 bus network shown in Fig. 1 is considered for analysis. If a fault is initiated between nodes 22 and 23, the possible paths are as follows:

- 23-22-21-20-13-12-11-10-9-8-7-6-5-4-3-2-1 (Weight=16)
- 23-22-21-20-19-18-17-16-15-14-13-12-11-10-9-8-7-6-5-4-3-2-1 (Weight = 22)
- 23-22-21-20-19-18-17-16-15-69-68-67-66-11-10-9-8-7-6-5-4-3-2-1 (Weight = 23)
- 23-22-21-20-19-18-17-16-15-69-68-67-66-65-64-63-62-61-60-59-3-2-1 (Weight = 23)

The shortest path identified using the proposed Dijsktra algorithm and Floyd-Warshall path recovery algorithm is as shown in Fig. 2 (Table 1 and 2). This shortest path involves 17 nodes and its path weight is 16. Power supply is ensured by the proposed algorithm to maximum number of connected loads.

The IEEE 16 bus distribution network shown in Fig. 3 is considered for analysis. The Dijkstra and Floyd-Warshall algorithms were individually made to run for three different processors as listed below:

- Intel(R) Core Pentium, 1GB RAM, CPU@ 1.30 GHz
- Intel(R) Core (TM) i5, 4GB RAM, CPU @2.20 GHz
- Intel(R) Core (TM) i3, 8GB RAM, CPU @1.90 Ghz

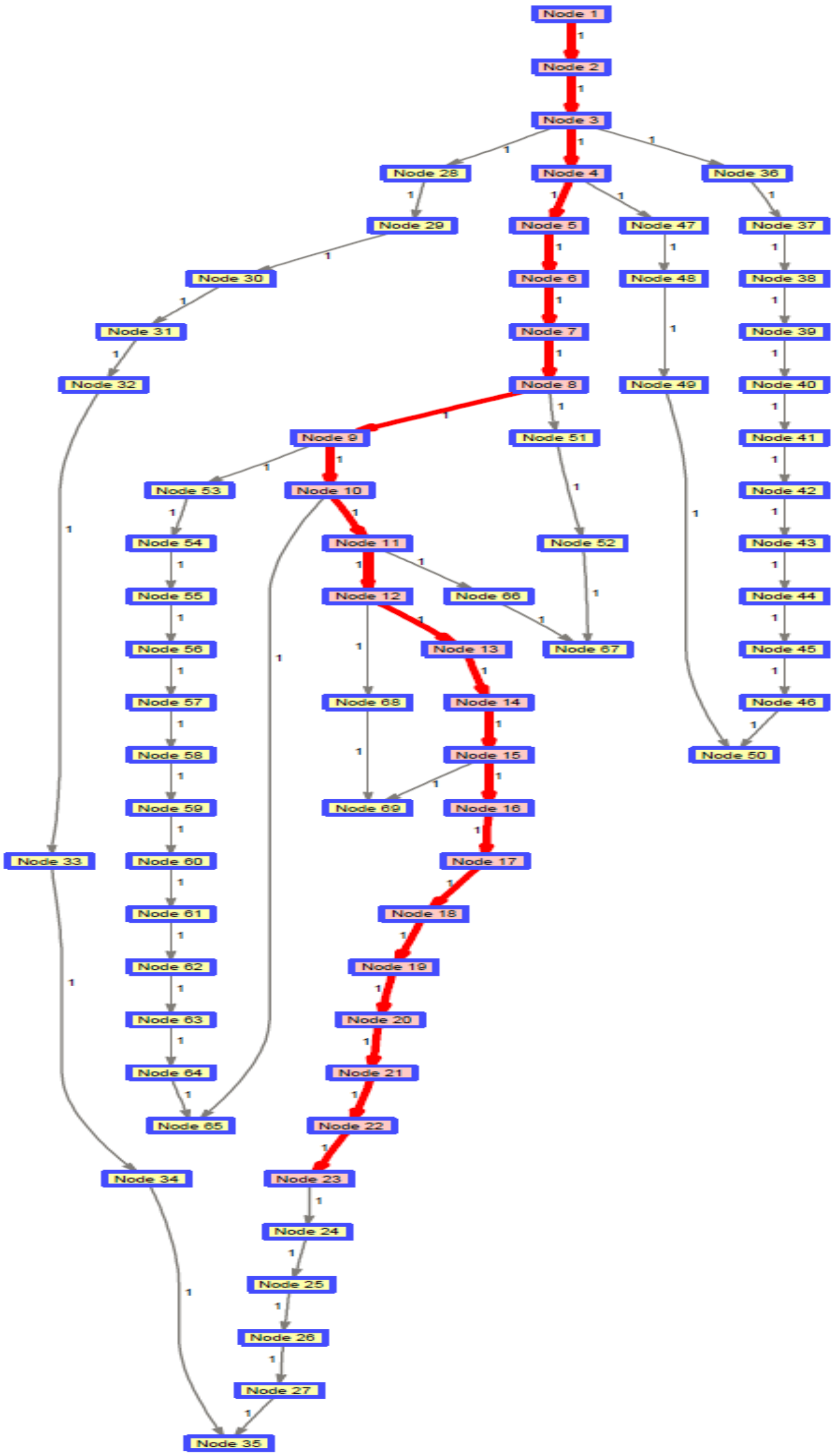

Fig. 2: Shortest path identification using proposed Fredman and Floyd-Warshall and Dijkstra's algorithm

Let us assume a fault occurs between node 13 and 3, then the shortest path is as shown in Fig. 4. The run time consumed by Dijkstra and Floyd-Warshall algorithm during shortest path identification is tabulated.

Table 1: Runtime for Dijkstra algorithm

Error nodes	Processor	Run time
3	Intel(R) Core Pentium, 1GB RAM, CPU@ 1.30 GHz	2.79714e+005
3	Intel(R) Core (TM) i5, 4GB RAM, CPU @2.20 GHz	1.329360e+005
3	Intel(R) Core (TM) i3, 8GB RAM, CPU @1.90 GHz	2.086279e+005

Table 2: Runtime for Floyd-Warshall algorithm

Error nodes	Processor	Run time (clocks per sec)
3	Intel(R) Core Pentium, 1GB RAM, CPU@ 1.30 GHz	2.98658e+005
3	Intel(R) Core (TM) i5, 4GB RAM, CPU @2.20 GHz	1.53036+e005
3	Intel(R) Core (TM) i3, 8GB RAM, CPU @1.90 GHz	2.36413e+005

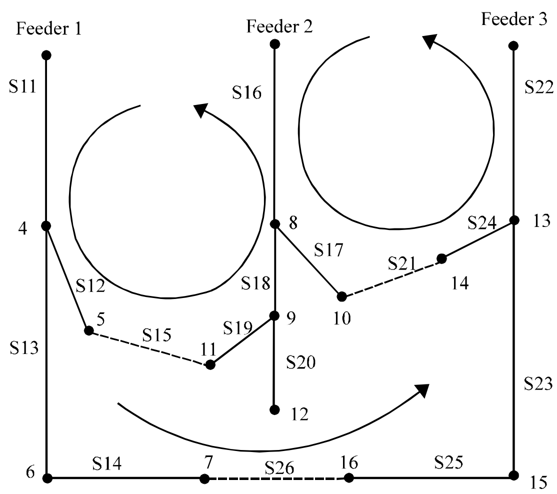

Fig. 3: IEEE 16-bus distribution network

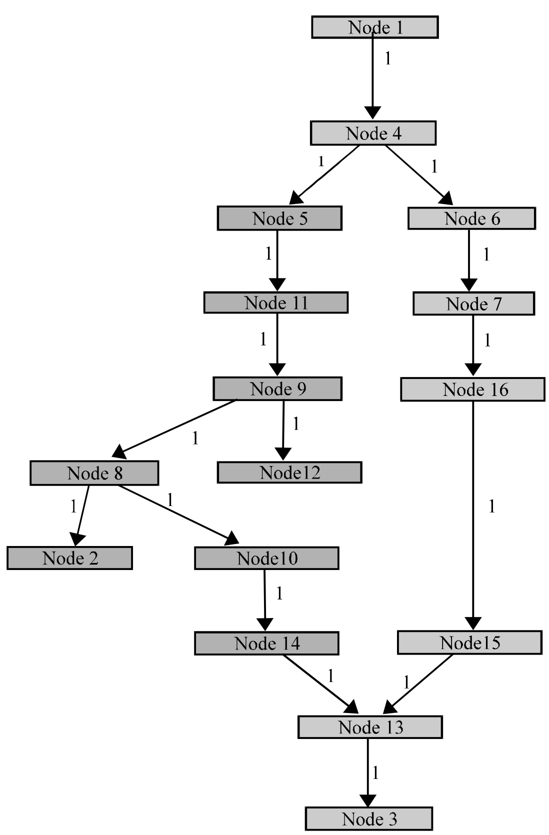

Fig. 4: IEEE 16 bus shortest path network

CONCLUSION

The protection of reconfigurable microgrid is a challenge for the power system engineers. This study proposes Fredman-Tarjan algorithm for identifying the active nodes of the network. If fault occurs, the shortest path to isolate the fault from the healthy part of network is deduced using Dijkstra or Floyd-Warshall algorithm. It is observed that only a minimum portion of network maybe disconnected during the fault clearance.

It can be concluded that, the algorithms were most efficiently and quickly performed by the Intel Core i5 processor followed by the Intel Core i3 and Intel Pentium processors, respectively. It is evident from the result that for a dense graph network Dijkstra algorithm is much faster in fault clearance than the Floyd-Warshall algorithm.

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