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Power system restoration in distribution network using minimum spanning tree - Kruskal's algorithm

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ABSTRACT

Events such as natural and manmade interference, line, transformer and feeder outages that occur in electric power distribution system negatively impact the continuity of power supply, thus affecting the power demand supply as well as customer's satisfaction. In that cases, the restoration of power needs to be carried out immediately in order to guarantee the system's reliability. The power flow path identification is considered as a difficult task especially in a huge system due to large number of switches. Kruskal's algorithm is presented in this paper to find the minimum power flow path in a power distribution network. The comparison of performance between presented Kruskal's algorithm and Binary Particle Swarm Optimization (BPSO) was made in solving a problem regarding network reconfiguration. The proposed load restoration approach is tested on IEEE 33-bus single feeder radial distribution system using MATLAB software. From the results, it is found that the presented Kruskal's algorithm was able to search for the minimal power flow path that contribute to loss reduction for power restoration after the occurrence of fault.

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1. INTRODUCTION

Distribution network delivers the electric power to various type of loads by considering capacity issues and voltage tolerances to ensure there are no interruptions in the flow of power. An outage due to unavoidable faulted events degrades the functionality of the electrical distribution system, thus disrupting the continuity of power supplied to the electrical consumers. As for example, on 30 to 31st July 2012, the largest electrical outage in history that involved 50 GW of load affected about 670 million people of northern India, which is around 9% of the world population [1]. Unpredictable interruptions that occur in a distribution system may hinder the task to bring back the power system immediately to its healthy state. Therefore, service restoration by switching operation needs to be done immediately in the loss area to guarantee load demand is met [2-12].

The switching operation main objective is to reschedule the loads efficiently by proper switching of distribution power lines which consists of sectionalisation switches and tie switches [13]. This is done to reduce the influence of faults on customers as well as improving the reliability of the distribution network. Reconfiguring the feeders in the distribution network will redistribute the load more evenly, therefore reduce the voltage fluctuation, preserving the load balance and minimize losses. Nevertheless, the process of restoring power is a tough task because radiality of the network, voltage drop and current limits has to be maintained [14]. Hence, minimum spanning tree-based approach is presented to discover the best power flow path.

A minimum spanning tree (MST) is a subset of the edges of an undirected graph that connects all the vertices together, without producing cycles and with the minimum total edge weight. The algorithm such as Dijkstra, Kruskal, Prim and Reverse-delete are the classic algorithm of the minimum spanning tree. Network reconfiguration is determined by altering the switches status whether it is close or open. [15] was looking for the optimum network reconfiguration with power loss minimization for the paper objectives. [16] presents Dijkstra's algorithm for network deduction and identification for optimal configuration of the reduced network. Prim's algorithm is proposed in [17] to find the power flow path in distribution network after an outage. Metaheuristic algorithm named Genetic Algorithm was implemented in [18] to select optimal solution based on fitness algorithm function. A new algorithm which is RAY algorithm was proposed in [19] to produce a minimum weighted spanning tree of the given graph with no direction pointed. [20] presented network reconfiguration based on Binary Particle Swarm Optimization (BPSO) that maximize the loads being supplied while ensuring voltage regulation is not violated and minimum loss of power is achieved through switching maneuver. [21] dealt with Kruskal's algorithm to solve service restoration problem. The idea of this paper is to cover the unsupplied area by restoring that area as much as it can after an outage and by finding the minimum switching order for the operational network. However, the problem formulation does not consider the voltage constraint during the load restoration.

Therefore, this research introduces Kruskal's algorithm which include voltage limit as part of the technical constraint. The objectives of this paper are to find the minimal power flow path that contribute to minimum power loss during load restoration in distribution network by using Kruskal's algorithm. The performance of the presented algorithm with Binary Particle Swarm Optimization (BPSO) is evaluated by solving a problem of network reconfiguration on IEEE 33-bus single feeder test distribution network.

2. PROBLEM FORMULATION

2.1. Graph Theory

Graph theory can be used to solve power restoration problem. The buses and feeder in a network is known as vertex while the distribution line is known as edge. A graph is categorized into undirected graph and directed graph. A directed graph is a graph where all the edges in that graph are directed from one node to another. In contrast, an undirected graph is a graph where all the edges are bidirectional. The terms involved in the implementation of Kruskal's algorithm is shown in Table 1.

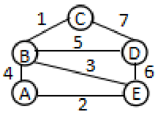
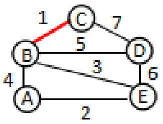
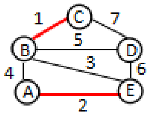
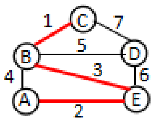
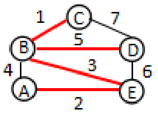
Table 1. Symbols in a Graph

Image	Description
(A)	Vertex or node
(A)——(B)	The connection line of node A and B is known as an edge. The graph is an undirected graph because there is no direction pointed to the node.
(A)—6—(B)	An edge that has a weight of 6 being connected between node A and node B

2.2. Kruskal's Algorithm

Kruskal's algorithm was discussed in 1956 [22]. It is one of the greedy algorithm in graph theory that finds a minimum spanning tree for a connected weighted graph. A minimum spanning tree (MST) is a subset of the edges of a connected, undirected graph that connects all the vertices together, without forming any cycles and with the minimum total edge weight [23]. Minimum spanning tree are divided into line-based MST algorithm and node- based MST algorithm. Kruskal's algorithm are classified under line-based MST algorithm. There are two conditions that must be fulfilled in Kruskal's algorithm [24], that are the line weight in a graph is sort in ascending order and an empty subgraph T is created. Table 2 shows a framework of Kruskal's algorithm.

Table 2. Framework of Kruskal's Algorithm

Image	Description
	Model example to implement Kruskal's algorithm.
	BC is the shortest edge with length 1. So, BC is highlighted.
	The second highlighted edge is AE that has a length of 2.
	The next shortest edge is BE with length 3. So, BE is highlighted as third edges.
	The next shortest edge is AB with length 4. However, AB will form a cycle if it were chosen. So, BD of length 5 is highlighted next to end the action as DE and CD will also form a cycle. The minimum spanning tree is found.

2.3. Load Restoration using Kruskal's Algorithm

Figure 1 shows the flowchart to find the path with minimum weight from the feeder to loads. The power system restoration in this paper is tested on a single feeder network. Line impedance are assigned as weight since the proposed algorithm is a weighted graph [21].

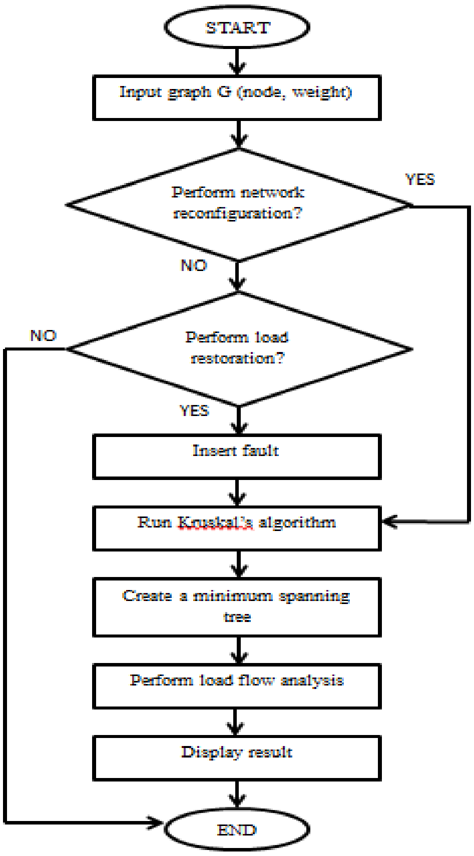


Figure 1. Flowchart of load restoration using Kruskal's Algorithm

The input data consists of the buses and lines data of the test system network. There are two case studies in this research which are network reconfiguration and power restoration. The requirement to run either one of the case studies in Kruskal's algorithm is decided based on the presence of fault in the system.

In order to perform power restoration, fault must be injected by increasing the weight of the line which refers to the impedances of the lines. Higher weight means higher impedances which indicate fault in the system [25]. Then the process will continue by implementing Kruskal's to get a minimum weight spanning tree. In Kruskal, the edge will be sorted in ascending order based on the line impedance. This algorithm will highlight the edge of the graph starting from the edge that has the least weight until it gains a minimum total edge weight as long as it does not form any cycle. For final result, load flow was performed from the minimum weight spanning tree obtained. Result achieved from the Kruskal's algorithm is then analysed in the form of table and graph.

2.4. Test Network

The IEEE 33-bus single feeder distribution system, 12.66 kV and 10 MVA, as shown in Figure 2 is used as the test system for this research. There are a total of 37 branches, 33 buses, 32 close switches and 5 open switches in the network. Branches S1-S32 indicate the sectionalizing switches while S33-S37 indicate the tie-line switches. The total of active and reactive load demand for this network is 3.715MW and 2.295MVar. The amount of active power loss and reactive power loss is 0.2024MW and 0.1349MVar respectively. Figure 3 shows the test network graph executed in MATLAB software.

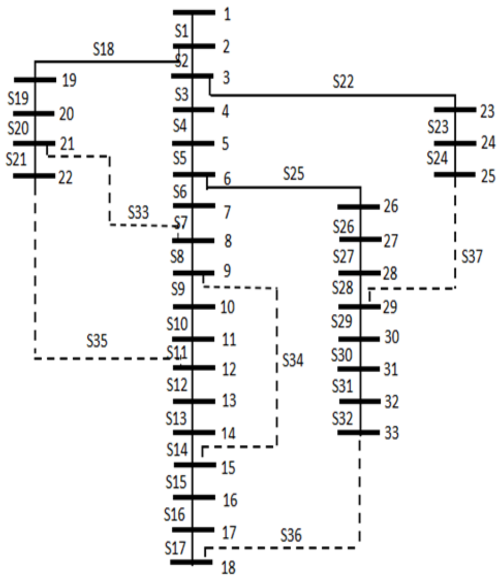


Figure 2. IEEE 33-bus single feeder system

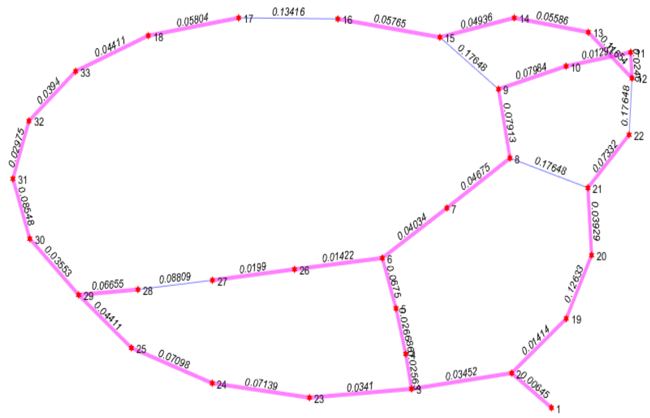


Figure 3. Test system in MATLAB

3. RESULTS AND ANALYSIS

Table 3 indicates the performance of the proposed Kruskal's algorithm with Binary Particle Swarm Optimization (BPSO). The minimization of power loss in a network is obtained by reconfiguring the network. At the same time, it also helps in improving the voltage profile and increases the system's reliability. After implementing this algorithm, the new set of open switches are S16, S27, S33, S34 and S35, while S7, S9, S14, S32 and S37 are the open switches selected by BPSO. From the result obtained, it is observed that both active and reactive power loss of the network using the proposed algorithm for the condition without fault are smaller than the base case. Kruskal's algorithm reduces the losses from 202.4 kW to 178.6 kW saving 23.8 kW. The real and reactive power loss for BPSO are lesser compared to proposed Kruskal algorithm. In terms of time duration, the time taken to reconfigure the network using Kruskal's algorithm is 0.8571s which is significantly lesser than BPSO that take 34.6300s. It is important to restore the unsupplied load quickly to maintain the system frequency. So, the implementation of Kruskal's algorithm in power distribution problem is one of the best way in reconfiguring the network for power restoration.

The acceptable voltage range in this test distribution network is between 0.9 pu to 1.00 pu. Figure 4 shows the results of voltage of the whole network using the proposed methodology was improved compared to base case voltage. The voltage profile in the figure reflects the lowest voltage across bus 18 as it is located at the very end of the feeder. The voltage at bus 18 shows an improvement from base case to Kruskal algorithm which is 0.9131pu to 0.9248pu. However, the voltage when applying BPSO method are better compared to Kruskal. It is proven that power loss is smaller with the increase of voltage and thus increasing the efficiency of the network. The voltage for both methods are still in the limit range between 0.90pu and 1.00pu**.**

Table 3. Result for Network Reconfiguration

Algorithm		Base case	Kruskal	BPSO
Tie switches		S33,S34,S35,S36,S37	S16,S27,S33,S34,S35	S7,S9,S14,S32,S37
Load	P (MW)	3.715	3.715	3.715
	Q (MVar)	2.295	2.295	2.295
Generation	P (MW)	3.916	3.893	3.854
	Q (MVar)	2.429	2.416	2.397
Ploss (MW)		0.2024	0.1786	0.1393
Qloss (MVar)		0.1349	0.1218	0.1022
Time (s)		-	0.8566	34.6300

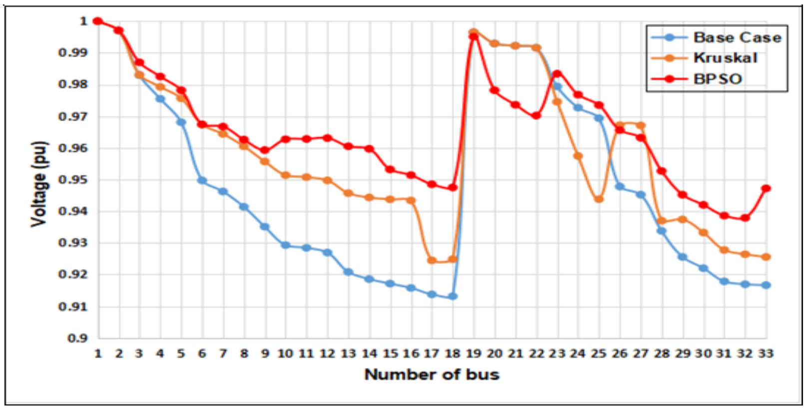


Figure 4. Voltage profile improvement

Table 4 indicates the result of single line outage of S13, S21 and S28 that occurs at a distribution system. In power outage condition, the impedance of the distribution line was increased to indicate that fault happens in that area. The line applied with fault will not operate, hence, making it to function as open switch. The result for Kruskal's algorithm is compared with randomly selected switch. It means that one out of five open switches in Kruskal's algorithm is selected randomly to observe the power loss between those cases. The result shows that the power loss for Kruskal's algorithm is less compared to randomly selected switches.

Table 4. Result for Single Line Outage

Outage line	Method	Switches				Power loss MW	Power loss MVar
S13	Kruskal	S27	S33	S34	S35	0.1971	0.1377
	Randomly selected switches	S25	S33	S34	S35	0.2072	0.1459
S21	Kruskal	S16	S27	S33	S34	0.1872	0.1275
	Randomly selected switches	S10	S27	S33	S34	0.2466	0.1788
S28	Kruskal	S16	S33	S34	S35	0.1757	0.1193
	Randomly selected switches	S8	S33	S34	S35	0.2415	0.1758

Figure 5 shows the comparison of voltage profile between Kruskal's algorithm and randomly selected switches when fault occurred at line 28. The voltage of a power system is stable under normal operating condition. However, the voltage will become unstable when the fault occurs in the system since the voltage drops below the acceptable limit. By using random switches selection, the lowest voltage value can be observed at bus 9 with 0.87 p.u. Meanwhile, by using Kruskal algorithm, the overall voltage profile is within the acceptable limit. This justify that Kruskal's algorithm can perform better than the random selection in restoring the load within the voltage limit.

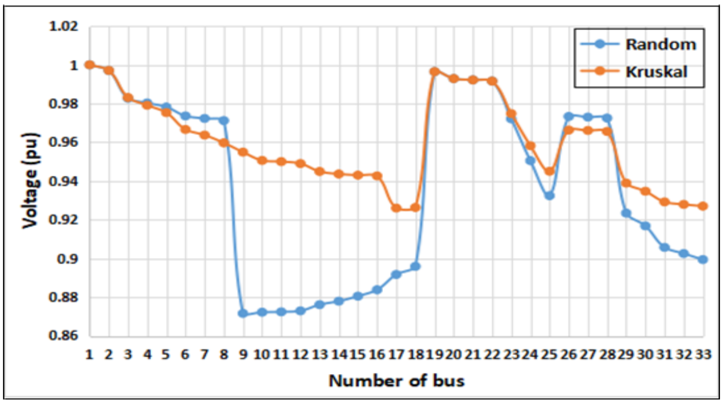


Figure 5. Comparison of voltage during fault at line S28

4. CONCLUSION

This paper proposes a power system restoration in radial distribution network based on Kruskal's algorithm. This algorithm determines the minimum flow path for power restoration in the out of service area. The effectiveness of the proposed algorithm has been carried out on IEEE 33-bus system where power is restored based on minimum line weight. From the test results obtained, the presented load restoration scheme is capable of finding the minimal path according to line weight. In addition, Kruskal's algorithm is better compared to Binary Particle Swarm Optimization (BPSO) in terms of time duration.

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