A Switch Placement Algorithm to Reduce the Impact of Distribution Network Maintenance in Continuity Indexes

Armando L. Keller, Rodrigo M. De Figueiredo, and Sandro J. Rigo

***Abstract*—The primary objective of power distribution utilities is to supply power to their consumers with minimal interruptions in both number and duration. These utilities are evaluated on continuity indices such as SAIDI and SAIFI. Sometimes, interruptions are needed to expand the network or for maintenance operations. This paper proposes an innovative method to evaluate the best place to install switches based on graph theory and centralities measurements to prevent disconnecting unnecessary customers in a maintenance event. The algorithm is demonstrated step-by-step with a simple example of a theoretical distribution network and then applied to the IEEE 123 bus test case for a comprehensive evaluation.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/8679

***Index Terms*—Distribution network, Optimization, Switch placement, SAIFI, SAIDI.**

I. Introduction

The continuity indexes for power distribution networks are essential information used to evaluate network reliability. Some well-known examples of such indexes are the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). Several approaches were already developed to support improvements in these index values and improve the network's overall performance, including identifying critical assets [1], approaches for reliability-centered maintenance [2], [3]. Among these initiatives, one can find switch placement, which is a practical optimization approach to enhance network reliability and reduce financial losses due to contingency conditions [4]–[7].

Different methods of optimization, such as Genetic Algorithms (GA) [8] [9], Binary Particle Swarm Optimization (BPSO), Modified Barnacles Mating Optimization (MBMO) [4], Ant Colony Optimization (ACO) [10], and others, are used to determine the optimal switch placement for the network. Those algorithms often solve np-complete problems where an exhaustive search is impossible in an acceptable time.

However, the performance of those algorithms depends on initial parameters like the number of particles on PSO or the mutation ratio on GA. There is little evidence in the literature on approaches dedicated to studying the network switch addition and configuration as a central attribute to be used with traditional algorithms for network optimization.

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This paper presents a method based on graph theory and centralities to determine where to place a switch on a network so that it could reduce the continuity index values in case of network maintenance. A case study is presented with the algorithm demonstration. The perfect case, but not economically viable, is to have switches just before and after each group of customers, allowing the minimal number of customers to be isolated in a network intervention. Executing the algorithm multiple times, in each execution, the place for a new switch is proposed until the perfect case is reached. The algorithm is explained and demonstrated in the material and methods section.

The main contribution of our work lies in proposing a graph theory-based algorithm to determine the positioning of a new switch in the distribution network to reduce the impact of maintenance in continuity indexes. This algorithm depends only on network topology and consumer data, such as the number of consumers connected to each bus and their estimated active power demand.

The paper is structured as follows. Section II describes every step of the algorithm along with an easy-to-follow example. Section III applies the algorithm to the IEEE 123 bus test case [11], considering a scenario with a planned interruption for maintenance and comparing the number of interrupted consumers and active power before and after the switch placement. Section IV presents the discussion and results of the proposed algorithm and their contribution to power distribution network planning.

II. Materials and Methods

This section shows the steps of the proposed algorithm alongside an application example for a small distribution network. All data of the example distribution network are provided so the tests can be reproduced regardless of the programming language or technology used. The three main steps of the algorithm are divided into network simplification, ranking subgroups, and switch placement. To avoid processing the full network and increase the algorithm execution time, the graph of the distribution network is simplified to a new graph with the same number of edges as the number of switches, where the customers between the same switches are grouped in a new node. With the simplified graph, each group of consumers, or the graph nodes, are evaluated by an importance rank that considers the number of minimal paths that this node is part of, the demanded power, and the number of consumers of each group. This rank allows the algorithm to search the optimal place for the switch in a small subgraph that is a small part of the original graph.

To place the switch, the algorithm replaces each edge of the subgraph with a switch for each execution and evaluates which position will result in the most balanced division, i.e., with the new switch, the subgraph could be split into two subgraphs with similar power and number of customers. This process uses graph centralities to focus the analysis on the most relevant part of the network, avoiding the need to test every available position. The following subsections describe these three main steps: the network simplification, the ranking of subgroups, and the switch placing.

A. Network Simplification

Distribution networks could be represented as graphs, where the vertices represent the network buses and the edges represent the lines and series equipment as switches and reclosers. To simplify the network for the first step of the analysis, every maneuverable equipment, such as switches and reclosers, will be opened, leading us to isolated connected groups. Each connected group of the graph is grouped, summing the characteristics as power and number of consumers. After that, the maneuverable equipment is switched to the closed state, connecting those simplified nodes.

To exemplify the simplification process, a simple network is represented in Fig. 1, where there are seven buses and five groups of consumers (from a to e). The lines ch1, ch2, ch3, and ch4 represent maneuverable equipment or switches. The consumer data is presented in Table I.

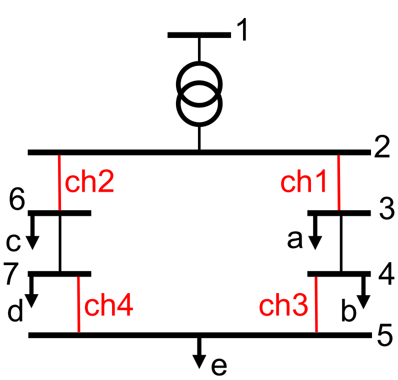

Fig. 1. Example network before simplification

TABLE I
CONSUMER CHARACTERISTICS FOR EXAMPLE NETWORK

Consumer group	Number of consumers	Active Power [kW]
a	3	35
b	4	50
c	1	20
d	8	90
e	6	75

Before the simplification, the graph representation of this network is shown in Fig. 2 with seven vertices and seven edges. Opening the switches on the example network forms four connected components subgraphs [12], [13] that could be grouped in four vertices for the simplified graph. Bus 1 and bus 2 were grouped in node '12', representing the source bus, and buses 6 and 7 were grouped in node '67', joining the characteristics of consumers 'c' and 'd'. The same goes for buses 3 and 4, which join the consumers 'a' and 'b' in node 34, and for bus 5, which keeps the 'e' consumer characteristics. The resulting simplified graph is shown in Fig. 3. Table II shows the resulting grouped network data.

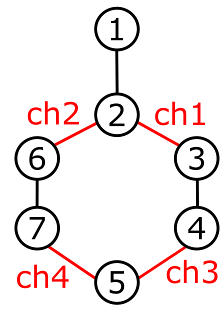

Fig. 2. Graph representation of the network

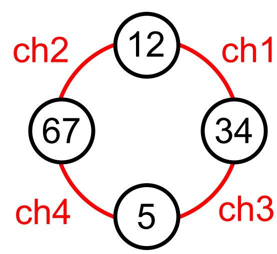

Fig. 3. Example of simplified network

TABLE II
GROUPED CONSUMER CHARACTERISTICS FOR EXAMPLE NETWORK

Node	Number of consumers	Active Power [kW]
12	0	0
34	7	85
67	9	110
5	6	75

B. Ranking Subgroups

Once the network is simplified, the criterion to determine the node relevance in the network must be defined. The betweenness centrality Bc [14] computes the shortest-path betweenness centrality for nodes or the relevance of the node in different possible network configurations and is defined by Equation 1 where V is the set of nodes, $\sigma(s,t)$ is the number of shortest (s,t)-paths. Active power should be considered to evaluate the impact on the Energy Not Supplied (ENS), as the number of customers should also be used to evaluate the impact on SAIDI and SAIFI indexes. Equation 2 is used to determine the rank $r(v)$ of each node v considering the active power Pw_v, the number of customers $Cust_v$, and $Bc(v)$. The active power and number of customers are normalized to have the same weight in the equation.

$$Bc(v) = \sum_{s,t \in V} \frac{\sigma(s,t|v)}{\sigma(s,t)} \tag{1}$$

$$r(v) = \frac{Pw_v}{\sum_{i=0}^{k} Pw_k} + \frac{Cust_v}{\sum_{i=0}^{k} Cust_k} + Bc(v) \tag{2}$$

For the example network, the rank values are shown in Table III where the node '67' has the highest rank value, i.e. he is the best candidate to contain a new switch.

TABLE III
RANK OF EACH NODE FOR EXAMPLE NETWORK

Node	Rank
67	1.053
34	0.613
5	0.242
12	0.166

C. Placing Switch

Once the node representing the subgroup where the new switch should be placed is chosen, it is necessary to find the place inside it to insert the switch. This will be the edge that divides the subgraph in the most balanced way. In case there are multiple nodes and edges, each edge of the subgroup should be evaluated, and the one that achieves the most balanced division of the subgroup, considering the active power and number of customers, should be the new switch. This could be achieved by copying the subgraph and removing one edge at a time, resulting in two new subgraphs where the absolute difference between their normalized active power and normalized number of customers is summed and stored in one array. The removed edge that produces the minimum value is the one that will produce the most balanced result. For the demonstration example, considering the node '67', which contains only two nodes (6 and 7) linked by one edge, this edge should be the new switch.

Placing the new switch between nodes 6 and 7, named ch5, allows us to isolate the consumer group 'c' or the consumer group 'd' separately in case of interruption for maintenance in one segment that impacts only one of them, thus reducing SAIDI, SAIFI, and ENS. This is the last step of the algorithm. The entire process could be executed until there are no more options to place new switches, i.e., every group of customers has one switch before and after them.

Executing the algorithm again with the new switch ch5 (between nodes 6 and 7) will result in ranks shown in Table IV, where it is suggested that a switch is placed in subgroup 6, but this subgroup contains only one node, so the next rank should be chosen, which is node '34'. Figure 4 illustrates the results.

This is the last feasible switch placement for this network once each remaining subgraph contains one or no groups of consumers or every group of consumers is separated by maneuverable equipment.

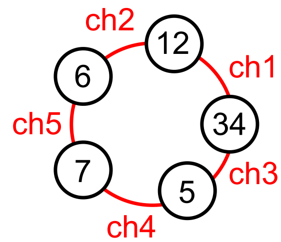

Fig. 4. Network after the switch placement

TABLE IV
RANK OF EACH NODE, FOR EXAMPLE NETWORK ON SECOND EXECUTION

Node	Rank
6	0.770
34	0.711
7	0.639
5	0.265
12	0.166

A new switch in the network increases the number of possible configurations two times; once a network with n switches has 2^n possible combinations of switch states, increasing the number of switches in one, the number of possibilities goes to 2^{n+1} or 2×2^n. Considering the network maintenance, the benefits of this new switch could be shown in two cases. The first one is maintenance, which requires disconnecting part of the network that will affect only the consumers connected to group 'c' (node 6), and the second one is the case which will require disconnecting only consumers from group 'd' (node 7). To evaluate the gains, the number of disconnected consumers which will affect the SAIDI and SAIFI indexes, and the disconnected active power, which will affect the ENS index, will be compared to the base case without the switch ch5. Even though the indices themselves are not used in the algorithm, the base information for the index calculation, such as the number of disconnected consumers and the amount of energy not supplied, are used.

The base case will disconnect the groups 'c' and 'e' for any maintenance that requires disconnecting the nodes 6 or 7. To disconnect any of these two nodes, the switches ch2 and ch4 should be opened, disconnecting both nodes. This means disconnecting nine consumers and 110 kW of active power.

With the switch ch5 positioned, it is possible to disconnect nodes 6 and 7 separately. In the first case, disconnecting only node 6, only one consumer and 20 kW of active power are disconnected, resulting in an 88.88% reduction in disconnected consumers, impacting the SAIDI and SAIFI indexes and 81,81% reduction in disconnected active power, impacting the ENS index. For the second case, disconnecting only node 7 will disconnect only eight consumers and 90 kW of active power, resulting in an 11.11% reduction in disconnected consumers and 18.18% reduction in disconnected active power. In both cases, the new switch allows us to isolate small network segments, increasing the continuity indexes.

This small network was presented to follow the algorithm in a simple example, but this could be applied to any distribution network. The following section presents a study case with the IEEE 123 bus test case.

III. Experiments

The IEEE 123 bus test case is used to demonstrate the application of the method proposed in this paper. The example does not provide the number of consumers, so one consumer is assumed for each 1 kW of active power. This network has five source nodes and 11 switches. The complete graph is presented in Fig. 5. Opening all the switches and applying the simplification step, the multiple nodes could be grouped into five groups from G1 to G5, as shown in Fig. 6. Table V shows the active power and number of customers for each subgroup for the base case before placing a new switch.

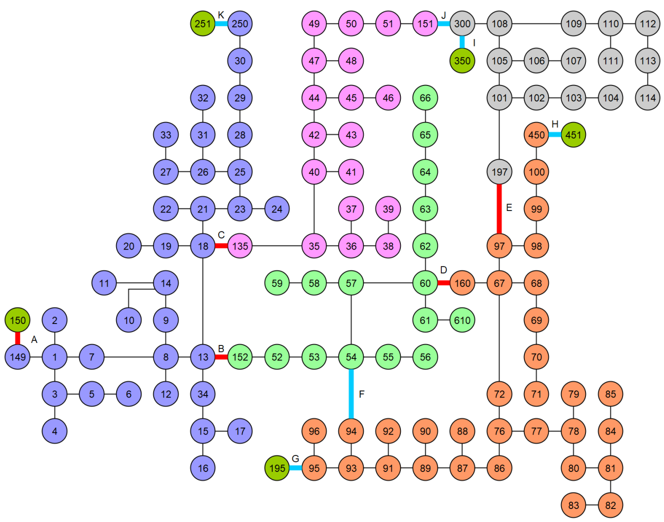

Fig. 5. Graph of the complete IEEE 123 bus test case.

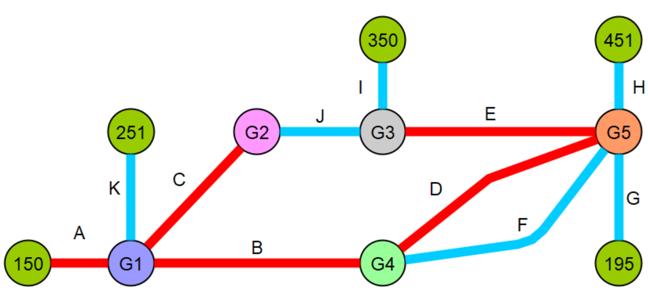

Fig. 6. Graph of the IEEE 123 bus test case after simplification.

TABLE V
Consumer Characteristics IEEE 123 Bus Test Case

Group	Number of consumers	Active Power [kW]
G1	760	760
G2	755	755
G3	320	320
G4	550	550
G5	1105	1105

In this case, maintenance will be simulated maintenance that should disconnect the nodes from 77 to 85, as highlighted in the lower right corner of Fig. 7. The switches D, E, F, G, and H should be opened to isolate this part of the network, disconnecting all the 1105 consumers and their respective active power.

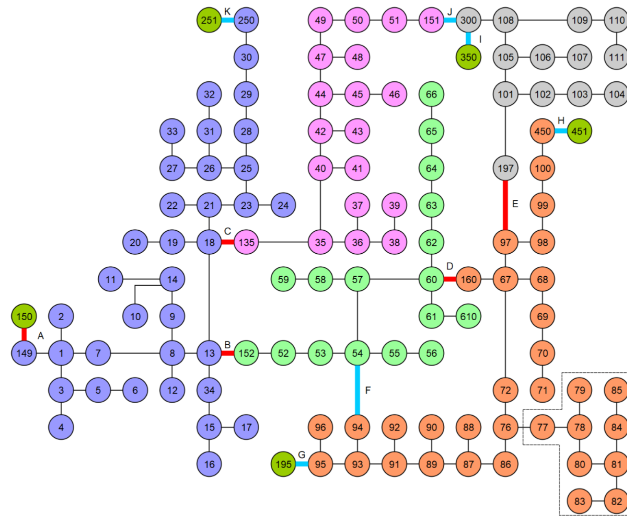

Fig. 7. Graph of the IEEE 123 bus test case with customers affected by maintenance highlighted.

The second step is to rank the simplified nodes; the results are shown in Table VI. The higher rank belongs to G5 with 1.105, so the new switch should be placed in this group.

TABLE VI
Rank of each Node for IEEE 123 Bus Network

Group	Rank
G1	0.879
G2	0.599
G3	0.488
G4	0.565
G5	**1.105**

The last part of the algorithm is to find the edge of the G5 subgraph, which will produce the most balanced network considering the number of consumers and active power. The algorithm indicates the edge between nodes 67 and 72 as the best candidate to become a switch. The new switch, named L, is shown in Fig. 8. This will split the G5 group into two groups G5a and G5b as shown in the simplified network in Fig. 9. The G5a group has 240 consumers and 240 kW of active power; the G5b group has 865 consumers and 865 kW of active power.

The initial case before the switch placement disconnects 1105 consumers. With the new switch, the group of consumers that should be disconnected is in the G5b group, so the switches F, G, and L should be opened to isolate 865 consumers instead of the original 1105 consumers from the initial case. Avoiding the disconnecting of 240 consumers and 240 kW of active power. This means a total reduction of 21.71% in impacted consumers and active power.

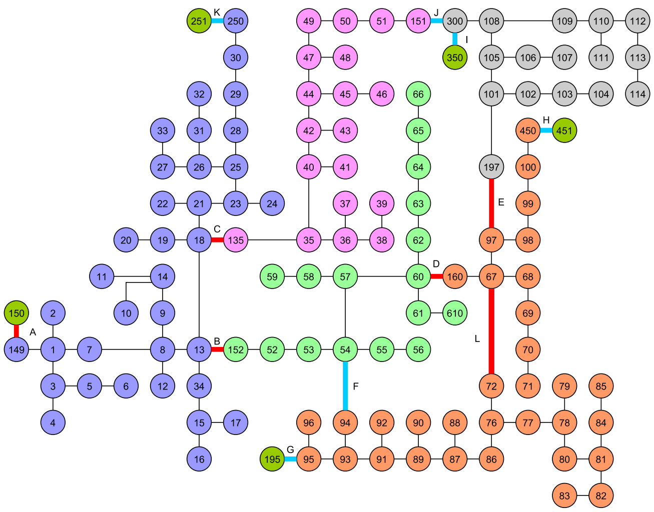

Fig. 8. Graph of the IEEE 123 bus test case with new switch L placed between nodes 67 and 72.

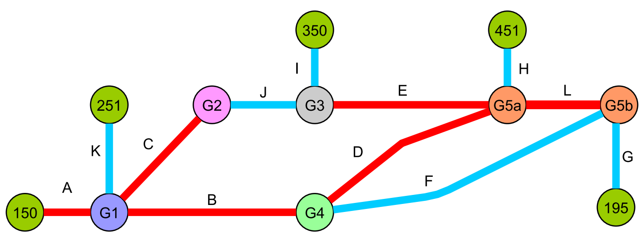

Fig. 9. Graph of the IEEE 123 bus test case with new switch L placed between nodes 67 and 72 simplified.

To evaluate the gains obtained by the proposed method, the execution time is compared with a deep search implementation, where all the possible edges are tested, for the IEEE 123 bus test case. The tests were performed on a computer with an Intel i7-10750H processor and 32 GB of RAM. The execution times statistics for 1000 executions of each implementation are presented in Table VII. The proposed method obtained an average reduction of 95,86% of the execution time when compared to the deep search.

TABLE VII
EXECUTION TIME FOR IEEE 123 BUS TEST CASE.

Algorithm	Min [ms]	Avg [ms]	Max [ms]	Std. Dev. [ms]
Deep Search	83,0	89,4	127,8	5,5
Proposed	3,0	3,7	16,5	1,1

IV. Conclusion

Power distribution networks could be complex systems once the network is modified every time a new customer is added or removed or the active power required is changed in addition to maintenance that sometimes requires interruption, impacting the continuity indexes such as SAIDI, SAIFI, and ENS. Inserting a new switch in the network doubles the possibilities of network configuration. The proposed method could be used to assist the power utilities in network planning, showing where to place maneuverable equipment such as switches and reclosers to reduce the impact of the maintenance in continuity indexes. The algorithm was demonstrated with an easy-to-follow example to show the application of every algorithm step. An experiment was performed in Section III with the IEEE 123 bus test case, which demonstrates that the algorithm could be applied to any power distribution or transmission network. The main advantage of this algorithm is that it does not depend on initial parameters like other optimization algorithms; it depends only on network topology and consumer and active power distribution. As future works are proposed to evaluate the solution considering the SAIDI, SAIFI, and ENS indexes, and comparing the performance of the algorithm with other meta-heuristics often used for optimization.

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