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A Self-Healing Based Smart Technique for Electric-supply Restoration Following a Permanent Fault in Smart Distribution Networks

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Abstract
The distribution network is a part of the electric network that directly provides energy to different types of customers. In a radial topology distribution network, there is only one path from a main substation to each load through overhead distribution feeders. This presents a number of advantages; among them is the restoration of the electric supply to all disconnected loads of the distribution network following a temporary fault by the use of reclosers. In the occurrence of a permanent fault, the electric supply to all download feeder sections is interrupted by a power outage of all loads until the maintenance crew moves to fix the faulty section. This reflects itself a negative impact on the network reliability indices, including the system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) indices. In order to improve the reliability indices of the distribution network following a permanent fault, restoration of the electric supply to the disconnected loads is due to seeking a smart distribution network. Three keywords describe the smart distribution network: automated, secure, and self-healing. This paper deals with achieving a self-healing distribution network to be a smart one. A self-healing is defined as recovering all out-of-service loads in the shortest time possible without violating the network operating constraints. This paper aims to propose a smart technique to recover the out-of-service loads following a permanent fault in the power distribution network.

1. Introduction

A guarantee of continuity of the electric supply to all customers in distribution network is an objective of the network to be smart whatever the conditions is normal or abnormal [1]. The fault in the distribution networks causes an interruption in the faulty location and all downstream customers [1-2]. The ability of the network to feed the end-users under abnormal conditions is called a self-healing network. The classical network to be smart, it should be supported with intelligent algorithms, equipment, and communication technologies [2]. Two factors help in measuring the reliability of the network. The system average interruption duration index (SAIDI) and the system average interruption frequency index (SAIFI). The self-healing algorithms provide improvements to system average

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interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) indices [3].

Sarma et al. proposed [4] a new technique based on transferring out-of-service unfaulty loads to other feeders in three stages, each stage is responsible for transferring loads with different possible maneuvers to grantee not causing constraints in the network. This proposed method is suitable for the network mentioned by the authors and not all different networks with no mention to the time taken by the three stages.

A combination between mathematical programming technique with an expert network has been proposed [5]. The technique is based on some if-then rules to solve the problem of constrains on load transfer. The proposed algorithm takes long time of computation.

The load service restoration problem was modelled [6] as a second order mixed-integer programming model, then solved with sub-techniques. The problem of the model took long-time took under processing.

Aoki et al. proposed [7] a method based on dual-gradient-technique to recover the out-of-service loads by using a single closing key in sequential manner. The issue of this method that many out-of-service and in-service loads were shed to avoid breaking the constrains.

A technique based on a breadth-first technique was proposed [8]. Firstly, a single closing then tries closing two open-closed switches and opening a normal-closed one in the path were made to prevent breaking radiality. The number of possibilities here may grow too fast in large networks.

This paper is aimed at proposing a smart technique to recover the out-of-service loads following a permanent fault in the power distribution network without violating the operating constraints.

The following sections of the present paper are as following. Section 2 represents the problem statement of the restoration challenges. Section 3 contains the mathematical model to the objective functions of the proposed technique. Section 4 includes the proposed method. Section 5 is consisting of the results and discussions of the proposed technique under testing. Sections 6 and 7 contain the conclusions and references of this paper.

2. The Problem Statement

In this paper, the power distribution network is represented by using graph theory. The graph (G) is a group of nodes/vertices (D) representing the feeders or the loads. These nodes are connected by using edges/arcs (V), which are simulated by switches, Fig. 1. In the graph representation of a radial distribution network, the switches are tendable for actuation either by a communication signal (SW_{comm}) or by a current exceeding pick-up value ($SW_{non-comm}$) [8-10]. Therefore, the graph is reduced to contain only switches of the type SW_{comm} to be controlled remotely. Fig. 2. For a node feeding a set of loads, each load is served by a non-communicated switch ($SW_{non-comm}$). However, the nodes themselves are served by SW_{com}.

The problem statement of electric-supply restoration is reviewed and the challenges facing the self-healing techniques are reported. The main objective of the restoration techniques is to minimize the outage percentage of the loads on occurring single or multi simultaneous faults without violating the network operating-constraints. These constraints represent the main challenges to be considered to achieve self-healing of a fault occurred in the distribution network. Fig. 3, shows a distribution network represented by a graph, where a green-square-node indicates a main feeder and a blue-circle-node points to a load. The nodes are connected through SW_{comm} switches where a solid line indicates the normally closed SW_{comm}, while the dashed one represents normally opened SW_{comm}. The interruption due to a fault at node F3 leaves the whole downstream portion of the network out-of-service (oos), as shown in Fig. 4. The protection Scheme forces switch (P_3) to open automatically leaving sectors 10, 11 and 12 out of service. The faulty node remains unsupplied with electric energy until the fault is fixed, while the healthy loads continued to receive electric supply to maintain reliability indices.

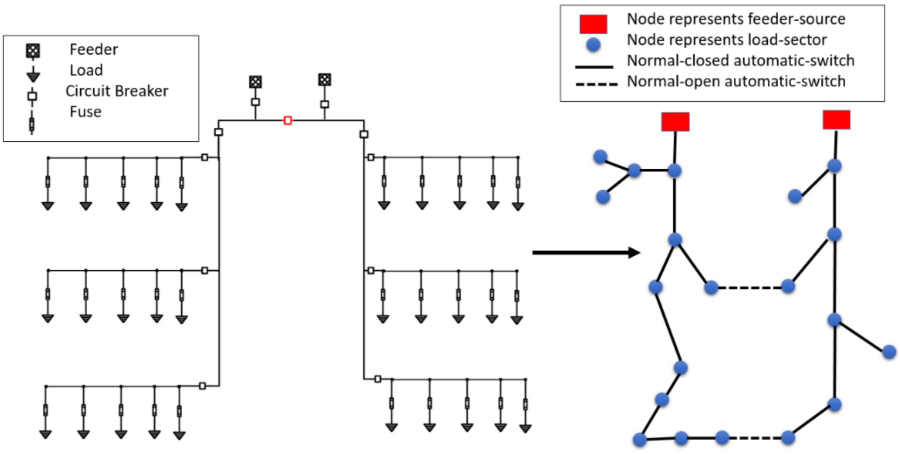

Fig. 1: Graph representation of a radial distribution network

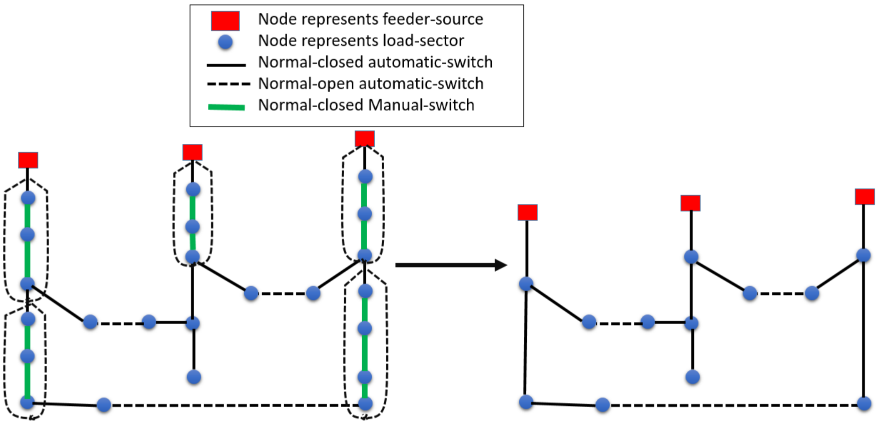

Fig. 2: A reduction for considering only maneuverable switches and loads

On closing switch (S_{9-10}) in Fig. 5, the loads 10, 11 and 12 are transferred to feeder (F_2) to remain served by electric supply. However, this maneuvering may break a constraint related to the operational limits of voltage, current and feeder capacity of F_2. This may end up by turning the feeder (F_2) out-of-service due to expected overloading condition and the supply restoration to all loads is not achieved.

On opening switch (S_{11-12}) in Fig. 6, the load imposed on the feeder (F_2) is mitigated by excluding load (12) which remains out-of-service. This maneuvering breaks again a constraint considering the priority concept of the load where load 12 may be a critical load such as hospitals. On opening switch (S_{6-7}) in Fig. 7 to keep the load (12) in-service due to its high priority to reduce the imposed load on F_2, this turns the load (7) to be out-of-service. This manoeuvring breaks again a constraint concerning shedding of healthy in-service node. The code of the proposed algorithm so far does not ensure all loads in-service. On opening (S8-6) and closing switch (S2-5) in Fig. 8 to make loads 5, 6 and 7 transferred to the feeder (F1), leaving enough capacity for the feeder (F2) to redistribute the loads among the feeders.

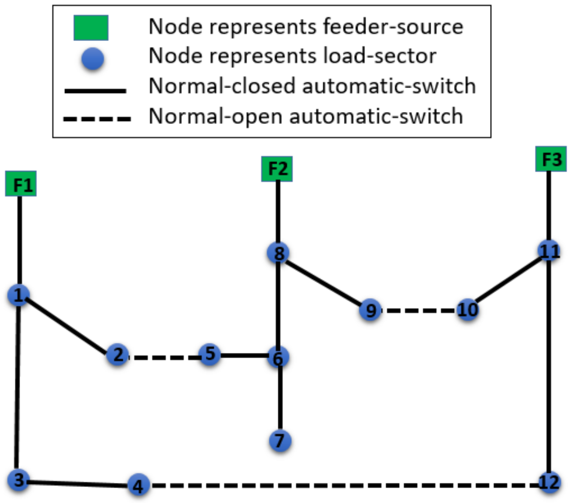

Fig. 3: Graph representation of a distribution network

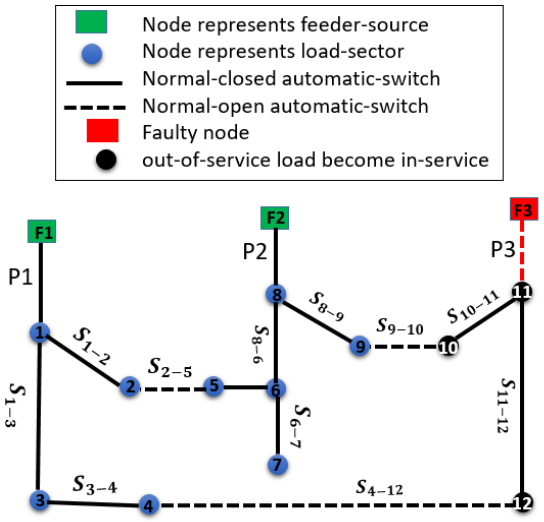

Fig. 4: Fault at node F3

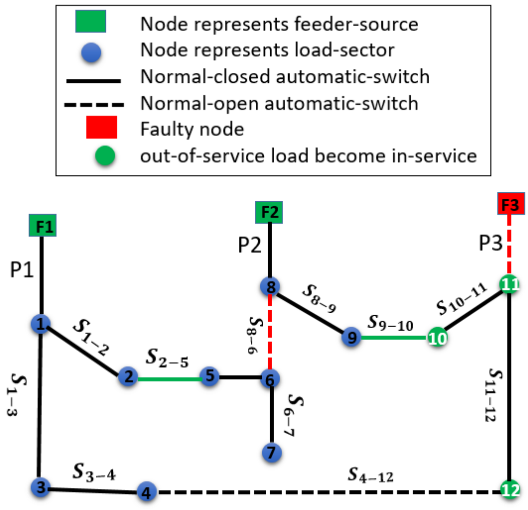

Fig. 5: Wrong manoeuvring after restoration oos loads

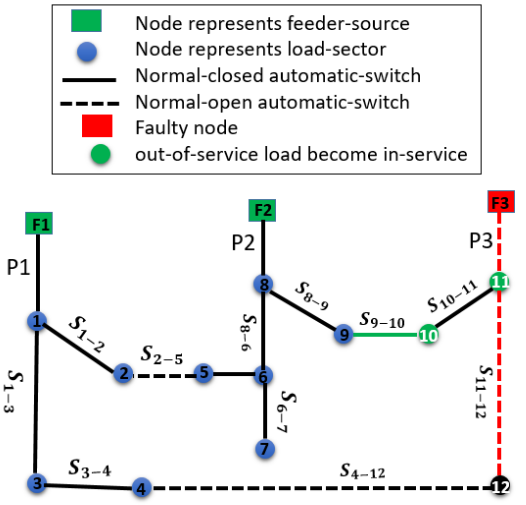

Fig. 6: Wrong manoeuvring after restoration oos loads

However, opening the automatic switch (S8-6) at first results in temporary disconnection of the loads 5, 6 and 7 until (S2-5) is closed with a subsequent violation of the reliability indices. On closing switch (S2-5), no load becomes out-of-service, but the network lost its radiality nature causing loss of coordination in the protection scheme or the two synchronous generators at F1 and F2 may not be in synchronism. Restoration aims at supplying the out-of-service loads in the shortest possible time without violating constraints such as voltage and current limits in buses and lines, feeder capacity, priority of the loads and network radiality [11-13].

Three indices evaluate the reliability of the distribution network [5-7]. Firstly, the SAIFI which represents the network average interruption frequency index, which provides information about the average number of interruptions after restoration, equation (1). Secondly, SAIDI which represents the network average interruption duration index, which describes the total time that loads became out of service due to interruptions after restoration, equation (2). Thirdly, ENS which represents the total energy not supplied index, equation (3) [14-16].

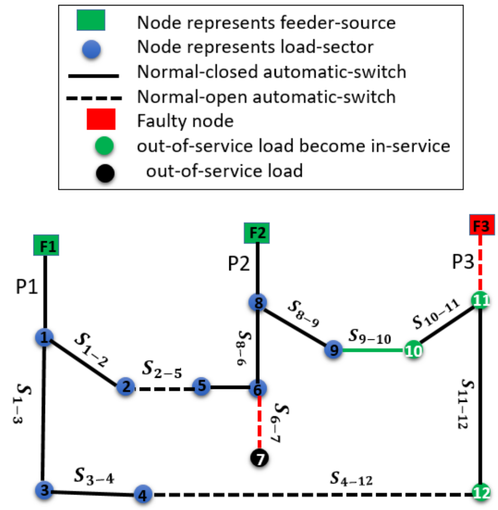

Fig. 7: Wrong manoeuvring after restoration oos loads

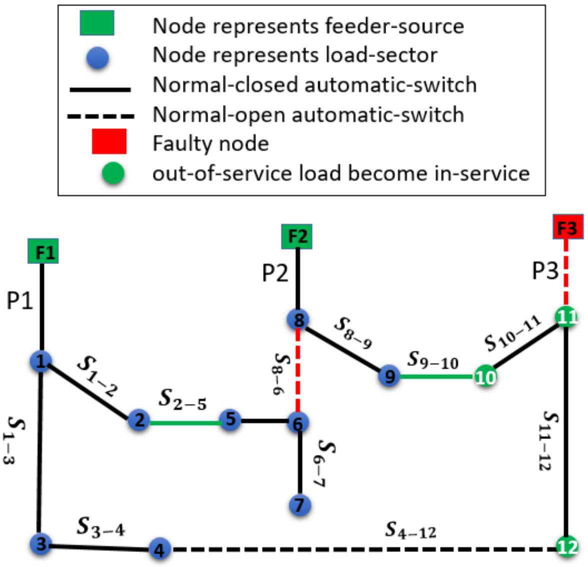

Fig. 8: Wrong manoeuvring restoration oos loads

$$\text{SAIF} = \frac{N_{(interruption)}}{n_{(customers)}} \tag{1}$$

Where: $N_{(interruption)}$: the total number of all interruptions after restoration and $n_{(customers)}$: the total number of connected customers

$$\text{SAIDI} = \frac{T_{(interruption)}}{n_{(customers)}} \tag{2}$$

where: $T_{(interruption)}$: the total duration of all interruptions after restoration.

$$\text{ENS} = \frac{U_{(not\ supplied)}}{n_{(customers)}} \tag{3}$$

where: $U_{(not\ supplied)}$: the total energy not supplied after restoration.

3. Mathematical Model

The proposed technique is modelled as a multi-objective function problem as follows:

Main function (f_1): Minimizing the percentage of the outage load following the occurrence of single fault or multi- simultaneously faults. In other words, the main objective function aims at restoring the electric supply for all outage loads without violating the constrains and expressed as follows [17-18]:

$$f_1 = minimize\left(\frac{L_{OOS}}{L_{tot}} x100\right) \tag{4}$$

where:

L_{OOS}: Number of out-of-service loads with application of the proposed technique

L_{tot}: The total number of out-of-service loads following fault occurrence.

The previous constraint functions to be taken in consideration as follows.

Function 2 (f_2): Rated capacity including the overload factor for all electrical equipment including feeders, transformers, cables…. etc must not be exceeded as expressed as follows [19]:

$$f_2 = I_k \leq I_{k(rated)} \tag{5}$$

where:

I_K: Current passes through branch K.

$I_{K(rated)}$: Rated capacity current of branch K.

Function 3 (f_3): The voltage must be within limits to avoid voltage sag or swell for every electrical equipment as expressed as follows [18-19]:

$$f_3 = V_{k(min)} \leq V_k \leq V_{k(max)} \tag{6}$$

where:

V_K: voltage at branch K

$V_{K(min)}$: Minimum acceptable voltage at branch K; equals to 0.9 pu.

$V_{K(max)}$: Maximum acceptable voltage at branch K; equals to 1.1 pu.

Function 4: Minimizing the total losses during restoration. If the proposed technique produced more than one maneuverer, the maneuverer that achieved the shortest path should be chosen.

Function 5: During restoration, high priority should be assigned to critical (important) load sectors.

Function 6: Self-healing should avoid shedding of in-service loads.

Function 7: Decisions through the proposed technique must guarantee radiality of the network.

4. Proposed Method

The proposed algorithm based on classification the switches into Six types, Fig.9.

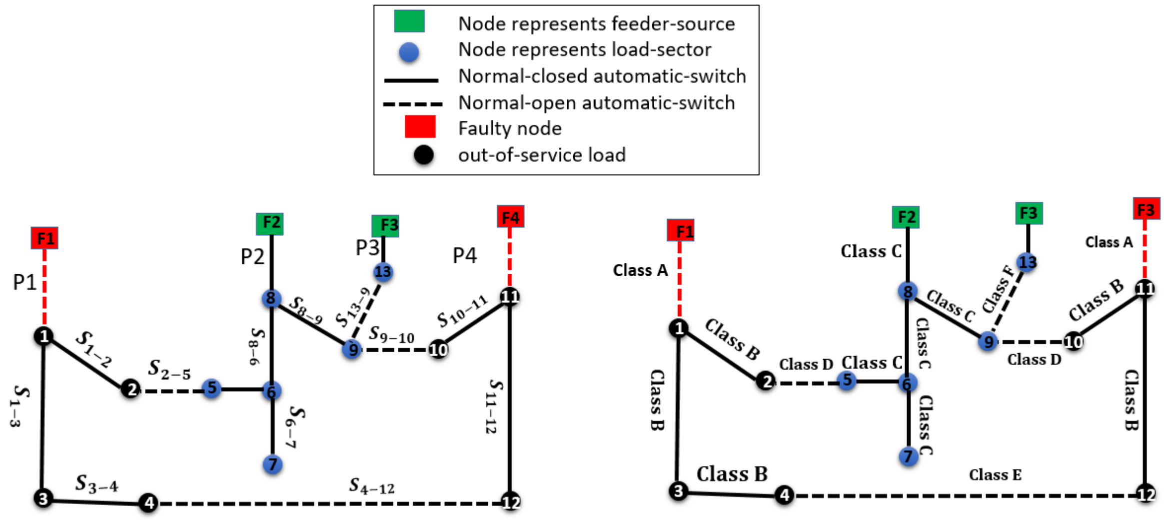

Fig. 9: Classification of the switches for the proposed technique

Class A switches are normally closed, open to clear the fault and send signal to a control unit. This is the first communicated switch (SW_{comm}), which operates following occurrence of the fault by the protection relays. Depending on the data received by the control unit about the first opened switch, the proposed algorithm treats this switch as related to class A to determine where the faulty load as well as the out-of-service loads are. The proposed algorithm will not give closure order to this switch before clearing the fault, i.e. the proposed algorithm is blocked against sending signals to class A switches.

Class B switches are normally closed and connect two out-of-service loads downstream for the same fault. These switches are used for shedding out-of-service loads when the supporting feeder is not able to recover all out-of-service loads without breaking constraints.

Class C switches are normally closed and connect two in-service loads to shed a less-priority in-service load for providing more capacity to the supporting feeder.

Class D switches are normally open switches connected between an in-service load and an out-of-service load. In the restoration process, they are the ones responsible for restoring at first the energy to the out-of-service load.

Class E switches are normally closed and connect two out-of-service loads due to different faults. In case one of the loads turns to be in-service, this type of switches can be ordered.

Class F switches are normally open switches connecting two in-service loads and used for load transfer from the supporting feeder to a neighboring one seeking an increase in its capacity.

The proposed method is explained in the following steps.

Step1: Initialize the data of the distribution network as a graph (G).

Step 1.1: Initialize the nodes (D) of the graph, which is either a feeder or a load.

Step 1.2: Tag each feeder with its loads.

Step 1.3: Initialize the vertices (V) of the graph, which are either normally opened or normally closed.

Step 1.4: Tag each two nodes with its edge.

Step 1.5: Define the priority of each node (High or low)

Step 1.6: Define the constraints (node capacity currents, limited voltage, radial constrain)

Step 2: Classify each edge, e.g. class C or class F only for the normal-operation case.

Step 3: Check if there is a fault that occurred or more than one fault.

Step 3.1: Determine the faulty load.

Step 3.2: Determine the out-of-service loads.

Step 3.3: Classify the switches into the classes A through F.

Step 4: Do not close class A switches until receiving a signal saying that the fault is fixed to back to the initial condition as stated in step 1. (Step 1)

Step 5: Close class D switches, check if there is a constraint in breaking.

Step 5.1: If any switch class E becomes class D, close it.

Step 5.1: If the constraint of the feeder capacity is breaking, close switches class F.

Step 5.2: If the constraint of the feeder capacity is breaking a gain, open switches class C depending on the priority level.

Step 6: Generate the output in a sequence (sorted)

5. Results and Discussion

To test the proposed technique, many failure maneuvers are applied to observe the performance of the proposed technique taking into consideration single and multiple failures. Two scenarios are discussed in the following sub-section.

The proposed technique is applied to one of the IEEE distribution networks. Firstly, network S1 includes 4 feeders, 703 load sectors and 117 non-communicated switches as well as 13 remotely communicated switches. Secondly, network S2 contains 7 feeders, 21,633 load sectors and 2,768 non-communicated switches as well as 40 remotely communicated switches. The testing considers only remotely communicated switches.

5.1. Maneuverer 1: Single failure on network S1

In Fig. 10, nodes F1 through F4 are feeders. In the first scenario, it was considered a single fault at load 1, this is why the protection relay forces to open the communicated switch P1 at the output-terminals of feeder F1, Fig. 11. The opening of P1 is the only data sent to the proposed technique. The faulty load and all its downstream loads are interrupted; 2, 3 and 7. The proposed technique follows the coordination of the protection devices. As P1 is opened, the proposed algorithm knows that the fault must be before load 1. So, the faulty zone is at load 1 or the feeder F1. The proposed technique generates the following output.

[1] open automatic switch S_{1-3}
[2] close automatic switch S_{7-9}
[3] open automatic switch S_{1-2}
[4] close automatic switch S_{1-10}, Fig. 12

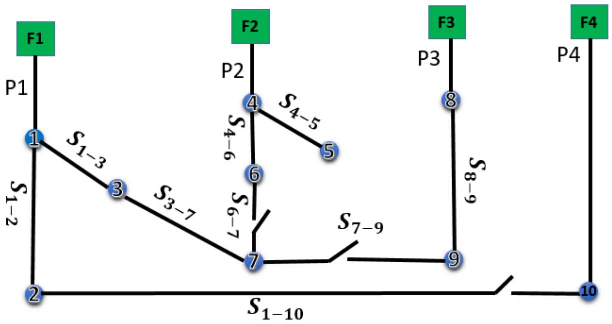

Fig. 10: maneuverer 1: Single failure on network S1

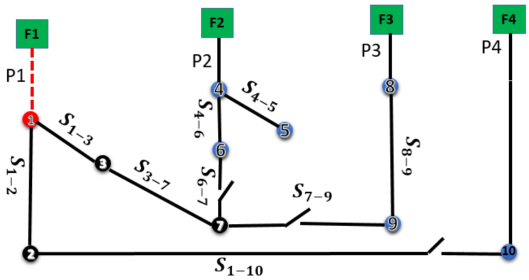

Fig. 11: maneuverer 1: Single failure on network S1

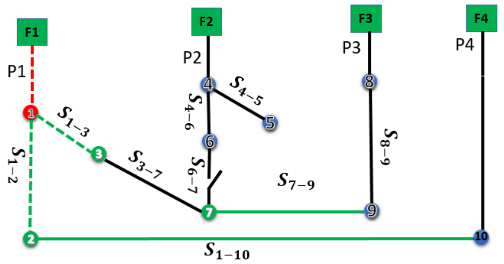

Fig. 12: maneuverer 1: Single failure on network S1

The proposed technique does not generate the following output because the feeder F2 is overloaded.

[1] open automatic switch S_{1-3}
[2] close automatic switch S_{6-7}
[3] open automatic switch S_{1-2}
[4] close automatic switch S_{1-10}, Fig. 13

In steps 1 and 2, the proposed technique recovered approximately 67% of the out-of-service loads. In steps 3 and 4, the proposed technique recovered approximately 33% of the out-of-service loads. This is why the proposed method is interested in saving the largest loads first.

5.2. Maneuverer 2: multi-failures on network S1

In the second scenario, it is considered a multi-fault at loads 1, 2 and 9. This is why the protection relay is forced to open the communicated switch P1, S_{1-2} and S_{8-9}, Fig. 14. The opening of P1, S_{1-2} and S_{8-9} are the data sent to the proposed technique. The faulty load and all its downstream loads are interrupted; 3 and 7. The proposed technique follows the coordination of the protection devices. As P1, S_{1-2} and S_{8-9} are opened, the proposed algorithm knows that the fault must be at loads 1, 2 and 9, consequently. So, the faulty zone is at load 1 or feeder F1 and load sector 2 as well as load sector 9. The proposed technique generates the following output.

[1] open automatic switch S_{1-3}
[2] open automatic switch S_{3-7}
[3] close automatic switch S_{6-7}, Fig. 15

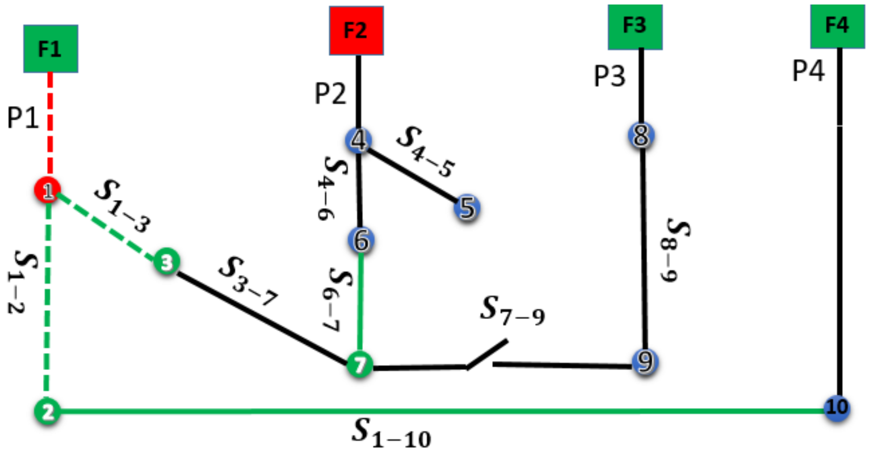

Fig. 13: maneuverer 1: Single failure on network

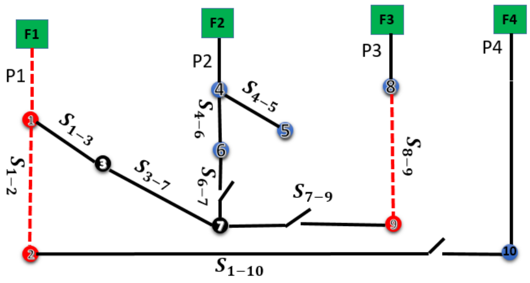

Fig. 14: maneuverer 2: multi-failures on network S1

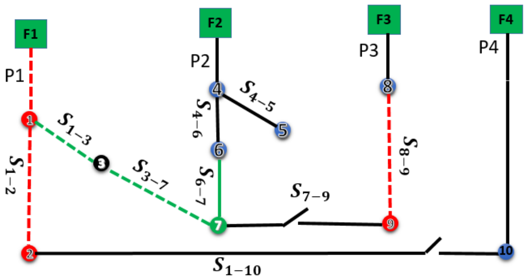

Fig. 15: maneuverer 2: multi-failures on network S1

The proposed technique recovers approximately 92% of the out-of-service loads. The secret behind opening the automatic-switch S_{3-7} is that the feeder F2 is overloaded. The proposed algorithm opened the communicated switch S_{3-7} not the non-communicated switch S_{4-5}, because the input data states that load sector 3 is lower in priority than the load sector 5.

6. Conclusions

A self-healing technique for a radial distribution network is proposed. The proposed technique is based on a code that classifies the communicated switches into six types. The proposed technique is based on successive manoeuvrings following the occurrence of the fault in the distribution network. The adaptive technique shows its success in not violating constraints during the restoration process. These constraints include feeder capacity, whatever current or limits of voltage as well as the priority of the load while maintaining the system radiality.

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