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Service Restoration in the Distribution System with Voltage Control Devices using Improved Sequential Opening Branches (ISOB)

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Abstract: *When a line, transformer, or feeder blackout occurred in the power system, service restoration was managed to optimal radial topology to restore maximum out-of-service loads with less switch operation and return the system to a healthy operation. This paper presents a new improved sequential opening branch (ISOB) algorithm to propose a solution for service restoration in power distribution systems by considering On-Load Tap Changer (OLTC) and Capacitor Bank (CB) operation at two different load levels with normal load and heavy load. The proposed method aims to minimize the percentage of voltage deviation index which is a measure of how much the voltage on a feeder deviates from the nominal voltage as the objective function. To ensure that the voltage levels remain within acceptable limits during service restoration, several tests are carried out on IEEE 33-bus and a 70-node system for multiple-fault scenarios.*

Keywords: Service restoration, OLTCs, CB, ISOB, Voltage control devices

1. INTRODUCTION[1]

A promising approach is reacting to the consequences of an outage caused by a damaged or overloaded network component, which is necessary for the power distribution network's operation. It may take many hours to replace or repair the faulty component, affecting numerous consumers. To address these challenges, a variety of solutions are available. Service restoration is one of the fundamental processes in the operation of power distribution networks under emergency conditions. After the location and isolation of a permanent fault, service restoration defines the available resources to open or close the switches [1]. Furthermore, to solve the service restoration problem, the authors [2] applied an analytic approach and a practicable heuristic graph-based method to find the best sectionalizing switch (SS) and minimize voltage drop. The author [3] introduced a novel mixed-integer second-order cone programming model to address the issue of the best restoration of distribution networks. The model takes into account not only network reconfiguration but also the formation of microgrids by minimizing the total de-energized load and the number of switching operations as the restoration plan's objective functions. To date, a number of researchers have employed Mixed-Integer Second-Order Cone Programming (MISOCP) for achieving optimal service restoration, including the authors [4] utilized this model to determine the best way to regulate distributed generators (DGs), voltage regulators (VRs), on-load tap changers (OLTCs), and capacitor banks (CBs) in order to deal with the restoration problem in active distribution systems. The author [5] additionally provided evidence the MISCOP model challenge, which was resolved with the MATLAB interface YALMIP and the Gurobi solver. The suggested model takes into account plenty of self-healing actions for testing on actual 83-bus distribution networks, including as network reconfiguration, nodal load rejection, tap setting change of voltage control devices, and active/reactive power dispatch of DGs. Moreover, the paper [6] brought up a novel technique known as the modified sequential opening of branches (MSOB) for service restoration in order to minimize the number of switches operating and load shedding based on the under-voltage constraint. This technique aims to improve the power quality and reliability in distribution systems in the event that multiple faults occur at different load levels. Tests are

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conducted on the IEEE 33-bus and 69-bus distribution systems using this proposed approach. Lately, the authors [7] proposed a Modified Sequential Opening Branch (MSOB) algorithm for a service restoration method considering system load level with distributed generation (DG) integration to improve reliability and efficiency in distribution systems at different load levels, addressing the challenge of high load levels.

In additional, a new method of service restoration utilizes distribution network reconfiguration, Distributed Resource Elements (DERs), and capacitor banks, as well as a modified PSO algorithm for Boolean variables. The solution meets operational restrictions such as DER capacity, capacitor bank capacity, and network loading limits. It restores service to more consumers with less voltage fluctuation than traditional approaches when tested on a 69-bus distribution system [8]. Next, According to the authors [9], DG can make service restoration more challenging because it can lead to voltage swings and imbalances. The author proposes a technique for service restoration using active network management (ANM) in active distribution systems (ADS). The method considers coordinated switch control, DG, and OLTCs, and was tested on 135 and 540 buses with single failures.

Furthermore, the service restoration problem operates with an On-Load-Tap Changer (OLTC) simultaneously considering the minimum switching actions with the tap position of OLTCs to minimize the non-supplied loads, the number of switching actions, and the number of tap changes for system restoration after the location and isolation of a permanent fault by using method transform the original Mixed Integer Non-Linear Programming (MINLP) formulation into a convex optimizing [10]. Moreover, the restoration procedure for the non-suppler of the un-faulted area has been completed using the proposed approach Sequential Opening Branch (SOB) in [11]. However, the restrictions remain violet. The OLTCs are then utilized to improve system reliability and quality using newly obtained Tie-Switches (TS) to restore the non-suppler of the un-faulted region based on multiple objectives. The IEEE 33-node and IEEE 69-node standards were tested with two distinct load levels to examine the influence of the approach.

In addition, the study [12] proposes a Pareto local search function for locating distributed generators (DGs) and capacitor banks in distribution networks. The function is a modified version of the conventional Pareto local search function that is adapted to the problem's features. The suggested function produced Pareto optimum solutions with reduced overall cost, lower voltage variation, and improved reliability when tested on a 33-bus distribution system. This strategy can improve distribution system reliability, efficiency, and sustainability. Distribution network restoration (DNR) is the concept of isolating the fault location(s) and finding the optimal topology so that the operating point of the distribution network is optimum considering technical constraints are satisfied (voltage limits, current limits, and radial structure). DNR is achieved by opening the normally closed (NC) sectionalizing switches (SS) and subsequently closing the normally opened (NO) tie switches (TS) which is one of the most important ways to enhance system performance.

The fundamental contribution of this study is a novel improved sequentially open branch (ISOB) for the problem of service restoration in active distribution systems, which considers voltage regulation through the optimal adjustment of substation OLTCs and CBs in conjunction with the radial topology network during the restorative stage. The experimental results illustrate that the proposed technique allows for more load restoration in multiple-fault events.

The entirety of this paper is structured as follows: Section 2 describes the objective function and constraints of service restoration strategy, explains the conventional sequentially open branch (SOB) and the improved sequentially open branch (ISOB) for restoration, and the load shedding process. Section 0 illustrates the testing system architecture for a simulation. Section 4 provides the results and discussion. Section 5 shows the conclusion of the proposed case study.

2. METHODOLOGY

This section presents, that service restoration is more concerned with the voltage quality within acceptable limits to restore electrical service in the event of a power outage. In contrast, the optimal service restoration in the network reconfiguration of the distribution systems is planned to use an improved sequential opening branch (ISOB) algorithm.

2.1 Objective function

The main objective function of service restoration is to restore all loaded feeders in distribution systems by minimizing the percentage Voltage Deviation Index (VDI). Therefore, the optimization problem is formulated as follows:

$$minimize = \frac{VDI_{aft.}}{VDI_{bef.}} \quad \text{(Eq. 1)}$$

Where VDI_{aft} is the voltage deviation index after restoration and VDI_{bef} is the voltage deviation index before the event of fault occurrence.

Voltage deviation can be defined as the difference between the nominal voltage and the actual voltage as defined as the sum of the square value of the absolute voltage difference between the nominal voltage and the actual voltage for all buses in the system.

$$VDI = \sum_{i=1}^{N_{bus}} |V_n - V_i|^2 \quad i = 1, 2, 3, ..., N_{bus} \quad \text{(Eq. 2)}$$

Where the V_n is the nominal bus voltage, V_i is the measured voltage at bus *i*. N_{bus} is the total number of load buses.

2.2 Service Restoration Constraints

2.2.1. Power balance:

In all distribution networks, the power supply must be equal to the sum of the power consumption and power loss.

$$P_{supply}^{t} = \sum_{i=1}^{N_{bus}} P_{cons.,i}^{t} + \sum_{i=1}^{N_{bus}} P_{loss,i}^{t} \quad \text{(Eq. 3)}$$

$$Q_{supply}^{t} = \sum_{i=1}^{N_{bus}} Q_{cons.,i}^{t} + \sum_{i=1}^{N_{bus}} Q_{loss,i}^{t} - \sum_{i \in scap} Q_{loss,i}^{t} \quad \text{(Eq. 4)}$$

Where P_{supply}^{t} is the total power supply from the substation to outgoing feeders, $P_{cons.}^{t}$ is the power consumption at the node i, P_{loss}^{t} is the power loss in the branch connecting to sending bus i. Q_{supply}^{t} is the total reactive power supply from the substations to outgoing feeders, $Q_{cons.}^{t}$ is the reactive power consumed by load demand at node i, Q_{loss}^{t} is the reactive power loss in the branch connecting to sending bus i, and the Q_{i}^{SCB} is the reactive power injected by the shunt capacitors bank at node i.

2.2.2. Node Voltage Constraints:

The voltage magnitude V_i at each bus should operate within a specific limit during the operation of the system.

$$V_{i}^{min} \leq V_{i}^{t} \leq V_{i}^{max} \quad \text{(Eq. 5)}$$

Where V_{i}^{min} and V_{i}^{max} are the minimum and maximum voltage acceptable in the system, respectively. V_i is the bus voltage. The voltage limits at normal operating conditions are considered $\pm 5\%$ of the nominal voltage emergency conditions following standard IEEE Std. 1366-2012 [13]. V^{min} is 0.95 per unit and V^{max} is 1.05 per unit.

2.2.3. The OLTC transformer constraints:

The voltage on the MV bus of the substation transformer can be regulated to the desired value by installing OLTC at the HV/MV substation. The voltage at the HV side of the OLTC is assumed to be constant (1 p.u.). the constraint related to OLTC installed is modeled as follows [9]:

$$V_{i}^{t} = 1 + tap_{i,t} . \Delta tap \quad \text{(Eq. 6)}$$

$$tap_{i,t} \geq tap_{i,t}^{max}$$

Where V_{i}^{t} is the voltage magnitudes of bus i period t, $tap_{i,t}$ is the tap position of the OLTC installed at substation bus i at period t, and Δ_{tap} is the step voltage of the OLTC.

Using the presented formulation for a typical OLTC with $tap_{i,t} \in \pm 16$ positions for the tap, the highest inaccuracy is 0.1 that can be obtained for Δ_{tap} is 0.3125 percent of the rated voltage, presenting an acceptable trade-off between precision and complexity.

2.2.4. Capacitor Bank constraints:

Regarding the CBs, the amount of the reactive power changes at each step, $(Q_{i}^{SCB,t})$ is capacitor bank rating at bus i, which its not small, unlike OLTC. Therefore, the step change of CBs is to minimize the tap changes of CB should be modeled with interval t. and ΔQ_{i}^{cap} is step change of SCB at bus i. The model of CBs participating in the restoration process is as follows:

$$Q_{i}^{SCB,t} = \Delta Q_{i}^{cap} . n_{i}^{CB,t} \quad ; \forall i \in SCB, \forall t \quad \text{(Eq. 7)}$$

Where $n_{i}^{CB} \in \{0, 1, 2, ..., n\} \quad ; \forall i \in SCB$

2.2.5. Radial structure constraint:

$$N_S = N_{bus} - N_{br} \quad \text{(Eq. 8)}$$

Where N_S is the total number of substations, N_{bus} is the total number of buses, and N_{br} is the total number of branches.

2.3 Conventional Sequential Opening Branches (SOB) method

The Sequential Opening Branches (SOB) method is a conventional heuristic approach used in power system restoration operations following the isolation of faulty areas.

The detailed method of the SOB algorithm is as follows:

Step 1: All tie switches are closed to form a mesh system.
Step 2: The Newton-Raphson (NR) load flow method is implemented.
Step 3: A switch containing the smallest active power loss is opened.
Step 4: The system is checked to see if it has converted to the radial topology. If the system has not converted, Steps 2-4 are repeated. If the system has converted to the radial topology, the algorithm moves to Step 5.
Step 5: The optimal radial structure is given. Sequential Opening Branch (SOB) method.

2.4 Improved Sequential Opening Branch (ISOB) for Service Restoration

The improved sequential opening branches method (ISOB) is an updated approach from the modified sequential opening branches (MSOB) [7] and the sequential opening branches (SOB) which performs the distribution network configuration in service restoration. This method includes two stages, the first stage applies sequential opening branches considering utilizing normal opening or tie-switches types from the initial topology to opening for replacing the switch of the permanent fault, while the second stage applies sequential opening branches, to find a sectionalizing switch or normally closed types to exchange with a tie-switches type from the new topology obtained in the first stage, but exclude all the switch of the permanent faults. The details of the ISOB algorithm are obtained step by step as follows:

2.4.1. Step 1: Sequential Opening Branch only Tie-Switches types for service restoration

The status of all switches in this step is initially set to be closed which forms loops in the distribution network. in the first iteration, the status of the location of the permanent fault, where that switch is located, is changed to be opened (i.e., changed to be a new tie-switch), after all, switches at the location of the permanent fault opened, the next iteration would be opened the initial tie-switches before faults happened in the distribution system, with the minimum objective functions and repeated in the next iteration till the network becomes radial. The procedure of the ISOB algorithm in step 1, provided below as the flowchart in Fig. 1 and the describe of selecting the new tie-switches should be opened in service restoration to bring the system back to normal operation shall be as follows:

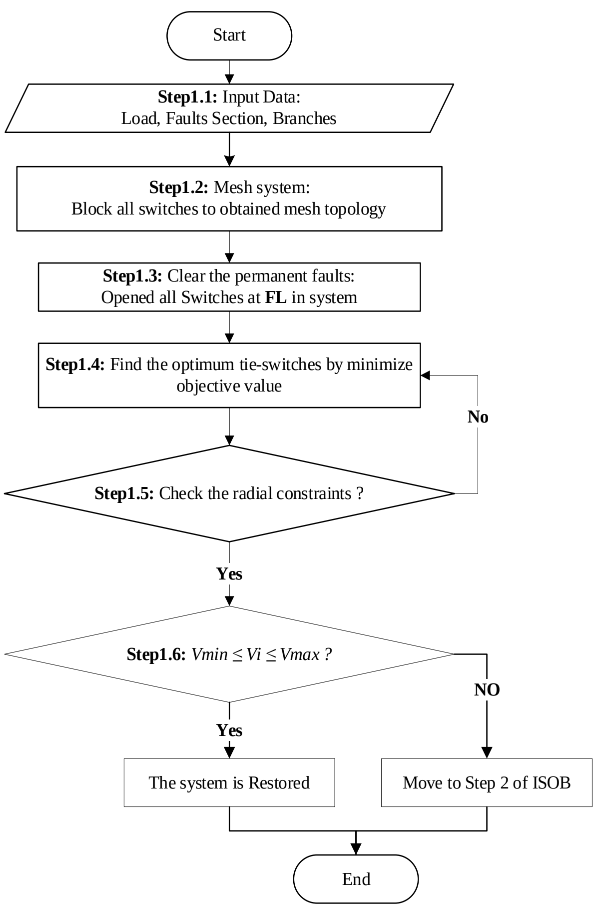

Fig. 1. The flowchart of Step 1 of The ISOB method.

Step 1.1: Obtain the generation, load, fault location, and topology information of a system.
Step 1.2: Find all the switches in loops and block all switches from the loops in the distribution network to turn the system to mesh topology.
Step 1.3: Let's set F_L to represent all switches at the fault section. Force all switches in F_L to be opened (i.e., changed to tie-switch (normally open)) to clear the permanent fault.
and $TS_{int}$to represent all the normally open switches (Tie-Switches) in the initial topology, as the second priority.
Step 1.4: Let's set TS_int to represent all the normally open switches (Tie-Switches) in the initial topology, Then Open a switch L_1 from TS_{int} in a loop, run power flow, and calculate the objective value (Eq. 1). Record the result with L_1 and then close the switch and open it back. Repeat this process until all the switches in the TS_{int} have been opened. Next, find the minimum objective obtained by opened L_1 and open the switch associated with this minimal objective.
Step 1.5: Repeat Steps 1.4 until the system is radial (Eq. 8) and the topology obtained from this step is called topology 1 (T_1).
Step 1.6: Check the constraints of limitation voltage (Eq. 5). If the new radial network obtained from the procedure above is operating at a voltage-acceptable level, the system is restored, else, move to Step 2 of ISOB.

2.4.2. Step 2: Sequential Opening Branch by exchanging sectionalizing Switch with tie-switch for service restoration

When step 1 of ISOB fails to bring the system back to normal operation, other different radial configurations in service restoration are generated from the initial restorative obtained from the first step searching for a better solution. This is achieved by opening a sectionalizing switch in the topology 1 (T_1) to exchange with a tie-switch (i.e., changing it to a tie-switch and that tie-switch changes to a sectionalizing switch) which leads to a different radial network configuration.

This procedure is applied to the other sectionalizing switches in topology 1 (T_1). Hence, the following procedure of ISOB's step 2 shall be applied below:
Step 2.1: After received data from Step1. Let's set S_s to represent all sectionalizing switches and TS to represent all tie-line from the topology1.
Step 2.2: Repeat the previous block of all switches to the mesh system.
Step 2.3: In addition, one of S_s switches is forced open, and one of TS switch turn to close then run power flow and calculate the objective function (Eq. 1) and save it with S_s and TS, next turn off that open and close switch back. Repeat this process until all S_s switches are opened and TS switches are closed.
Step 2.4: Find the minimum objective function of S_s with TS switches and turn that S_s to a new normally open (NO) with that TS to a new normally close (NC).

Step 2.5: run load-flow to calculate power loss, voltage deviation, and voltage profile, Check the voltage limit constraint (Eq. 5). If yes, move to the next Step 2.6. else,

update the topology (TS with new NO). and Repeat Steps 2.1-2.4 until we get the new TS which operates within the voltage acceptable (Eq. 5). Furthermore, if all TS in the topology 1 have been exchanged then save that last topology to represent Topology 2 for use in the load shedding process.
Step 2.6: Store the results of service restoration.
The procedure of the ISOB algorithm, provided below as the flowchart in Fig. 2 for step2, respectively, can help for a better understanding of above described.

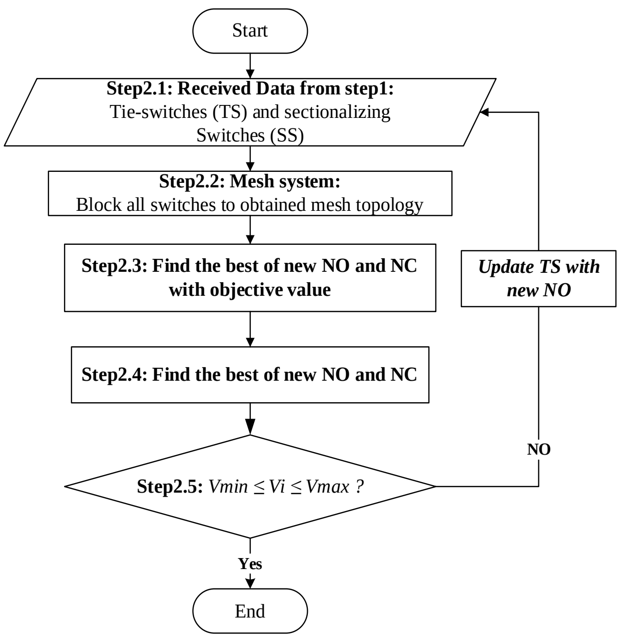

Fig. 2. The Flowchart for Step 2 of ISOB algorithm.

3. TESTING SYSTEM FOR SIMULATION

In this part, the proposed approach for the restoration system has been validated using simulation data, followed by a discussion. This proposal was developed using MATLAB 2021b and the MATPOWER 5.1 toolbox on a PC with a Core i5-9th Gen 2.4GHz CPU and 16 GB RAM.

3.1 Testing System Description

The performance of the algorithm has been tested on a radial IEEE 33-nodes testing system with one substation, illustrated in Fig. 3, it has 37 branches, 32 sectionalizing switches, and 5 tie-switches are 33 to 37. The network is 3.72 MW and 2.30 MVAr. The other testing system is a 70-bus distribution network with two substations, as shown in Fig. 4. The data of this system are provided by [14] . The active power losses for the initial network configuration are 227.5 kW with a nominal power of 1 MVA.

Furthermore, the initial topology has 11 tie-switches where located at switches 69 to 79, respectively. The specific information on OLTC tap and CB is shown in Table 1.

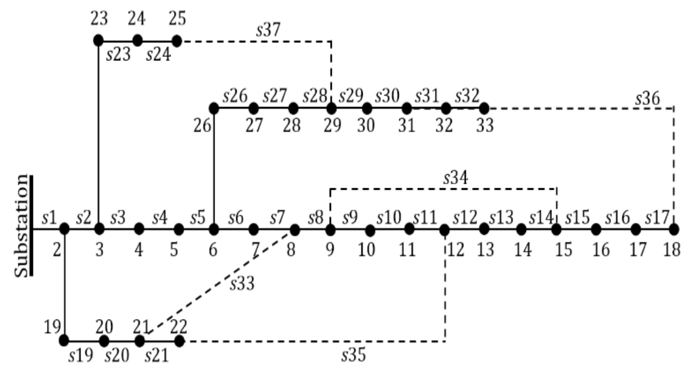

Fig. 3. The Initial Topology of The IEEE 33-Bus System

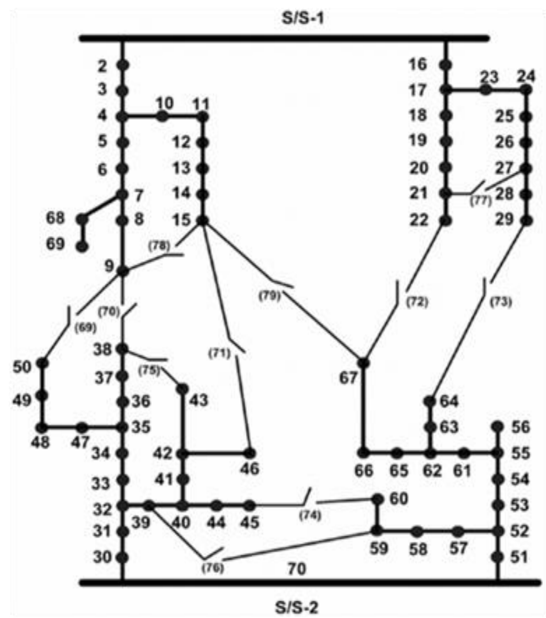

Fig. 4. The Initial Topology of the 70-Node System

Table 1. Specification Of The Voltage Control Devices

Items		CB	OLTC
System 33 nodes	Operation Mode	8 Steps with 0.3 Mvar/step	33 Steps, ± 16 tap positions with 0.003125 p.u./step
	Location	Node 30	Nodes 1
System 70 nodes	Operation Mode	8 Steps with 0.3 Mvar/step	33 Steps, ± 16 tap positions with 0.003125 p.u./step
	Location	Node 62	Nodes [1, and 70]

Two Cases are analyzed to examine the advantage of the ISOB with the on-load tap changer (OLTC) transformers and CB on the solution of the service restoration problem. The two cases are as follows:

- Case 1: The service restoration plan is determined based on the different load levels, while CB is not considered. The operation of the OLTC is considered.
- Case 2: The service restoration plan is determined considering the different load levels, OLTC and CB.

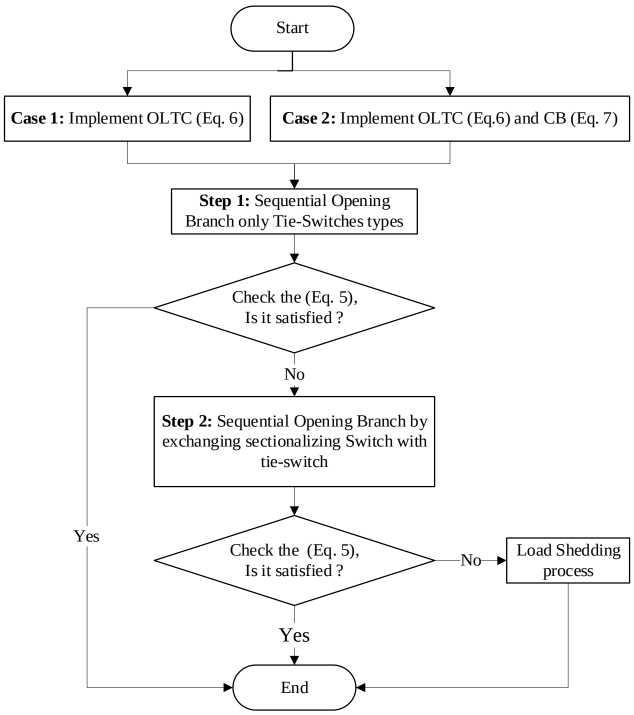

Fig. 5. The Flowchart for the proposed problem formulation using the ISOB algorithm.

3.2 Faults scenarios

The proposed in this study is evaluated with several permanent faults on lines {s14, s20}, and {s4, s8, s14} for the IEEE 33-bus system. while the 70-node system has three scenarios of case study as {s4, s36}, {s1, s26, s36, s62}, and {s4, s26, s36, s62}. These are the circumstances that result in greater amounts of disconnected load after the failure and occur at the beginning of the feeders.

4. RESULTS AND DISCUSSION

4.1 Case 1: Service Restoration with OLTC with different load levels

To further evaluate the efficacy of the proposed service restoration technique, many scenarios with several failures are simulated. Table 2 demonstrates two different scenarios for restoration issues in 33-bus and four different scenarios for 70-bus distribution networks without an integrated capacitor bank at both load levels as normal load and high load. The results presented in Table 2 show that in all circumstances, using the proposed in this study, ISOB operation during the restorative stage, it is feasible to restore more loads, although more switches in the system must be operated. For example, at 100% load, IEEE 33-bus testing requires two switch actions (turned switches s33 and s34 to sectionalizing switches) for scenario 1, and three switch operations (closed switches s34, s35, and s37) for scenario 2. Furthermore, the 70-bus testing system needs to operate switches four (by opening switches s31 and closing s71, s75, and s78), eight (by opening s2, with s31 and closing s71, s72, s75, s77, s78, and s79) and eight (by opening s9, and s40 with closing s71, s72, s74, s75, s77,s78 and s79) for scenario 1, 2 and 3, respectively.

When the load level increase to 130%, needs to operate four switches (by opening s28 and closing s33, s34, and s37) and five switches (opened s26 and closed s33, s34, s35, and s37) for the 33-bus system, while the 70-bus system requires to turn eight switches (by opening switch s41, s61 and s67 as well as closing switch s71, s72, s74, s75, and s78), eight switches (by opening switch s11, and s21 with closing s71, s72, s75,s77, s78 and s79), and fourteen switches (by opening switch s11, s37, s45, s47, s64 and s64 with also closing switch s69, s70, s71, s74, s75,s76, s77, and s78) switch operation for scenarios 1, 2, and 3, respectively. (Noted: the number of switching operations does not account for the operations to isolate the faulted section, present in Table 2 and Table 3). The minimum voltage magnitude achieved in the system was in the range of 0.9647 to 0.9686 p.u. for all scenarios of both systems, while the highest voltage magnitude obtained was 1.05 p.u. for the IEEE 33-bus system. Also, the lowest voltage magnitude ranged from 0.9527 p.u. to 0.9774 p.u., while the maximum voltage magnitude ranged from 1.0125 p.u. to 1.05 p.u. for the 70-bus system.

4.2 Service restoration with OLTC and CB

In this case, during the occurrence of the faults, Table 3 describes the service restoration integrating the on-load tap changer (OLTC) transformer with the capacitor bank (CB). By operating the OLTCs and CB at various load levels, it is feasible to simulate the proposed algorithm to give restoration plans that can reduce the voltage deviation and the number of switch operations in the system. For all situations, scenario 1 and scenario 2 of the IEEE 33-bus testing system require the operation of two (by closing S33 and S36) and three (by closing S34, S35, and S37) switches, respectively. While with scenarios 1, 2, and 3, the 70-bus system has to operate eight switches (by opening s28 and s55 but also closing s69, s70, s72, s73, and s78), five switches (by opening s31 and closing s71, s72, s73, and s79), and eight switches (by opening s3 and s31 as well as closing s69, s70, s75, s77, and s78). and at 130 percent of load levels, needs to operate two (closed s33, and s36) and four (closed s35, s36, and s37) switches, while the 70-bus system needs to operate four (by opened s32 with closed s71,s78, and s79), eight (by opened s33, and s67 with closed s70, s72, s73, s75, s77, and s79) and six (by opened s41 with closed s69, s73, s75, s78, and s79) switches to recover the system, respectively.

While the 130 percent of load levels, need to operate two (closed s33, and s36) and four (closed s35, s36, and s37) switches, while the 70-bus system needs to operate four (by opened s11 with closed s69, s78, and s79), six (by opened s37 with closed s69, s70, s73, s78, and s79) and eight (by opened s6 and s29 with closed s71,s73, s75, s77, s78, and s79) switches to recover the system, respectively. Additionally, the system's lowest voltage was in the range of 0.9671 p.u. to 0.9874 p.u. for the IEEE 33-bus system and 1.0313 p.u. to 0.9774 p.u. for the 70-bus system. The maximum system voltage was between 1.0313 and 1.05 p.u. for the IEEE 33-bus system and between 1.0000 p.u and 1.0406 p.u. for the 70-bus system.

According to Table 3 summary of the simulation findings for Case 2, some of the switches were required more operation than in Case 1. In contrast, the quantity of tap operations performed on the On-Load Tap Changer (OLTC) in case 2 is lower in comparison to case 1, along with a reduction in computational time. Consequently, these factors are anticipated to have an impact on the overall lifespan of the transformer. This outcome is unsurprising, given that the integration of a capacitor back (CB) during the resolution of service restoration problems may impede certain switch operations, number tap operation of OLTC and voltage profiles improvement.

Table 2. Service Restoration with OLTC at Different Load Levels

Case1: Service Restoration with OLTC												
System	Load Level	Scenario	Switching Operation	De-energized node	VDI	Obj.	OLTC at s/s-1		CB	Vmin [pu.]	Vmax [pu.]	Time Computation [s]
33-bus	100%	1	Closed: s33, and s34	None	0.0225	0.1517	+16		0	0.9680	1.05	3.98
		2	Closed: s34, s35, and s37	None	0.0239	0.2091	+16		0	0.9647	1.05	4.17
	130%	1	Opened: s28 Closed: s33, s34 and s37	None	0.0224	0.1617	+16		0	0.9662	1.05	6.03
		2	Opened: s26 Closed: s33, s34, s35, and s37	None	0.0199	0.1484	+16		0	0.9686	1.05	7.24
System	Load Level	Scenario	Switching Operation	De-energized node	VDI	Obj.	OLTC at s/s-1	OLTC at s/s-2	CB	Vmin [pu.]	Vmax [pu.]	Time Computation [s]
70-bus	100%	1	Opened: s31 Closed: s71,s75, and s78	None	2.0897	0.6179	+11	+16	0	0.9527	1.0500	25.93
		2	Opened: s2 and s31 Closed: s71,s72,s75, and s78	None	1.0617	0.3139	+3	0	0	0.9774	1.0481	26.45
		3	Opened: s9, and s40 Closed: s71, s72, s74, s75, s77, s78 and s79	None	1.2198	0.3606	-12	0	0	0.9582	1.0424	27.97
	130%	1	Opened: s41, s61 and s67 Closed: s71, s72, s74, s75, and s78	None	0.7684	0.2186	+16	+12	0	0.9564	1.0500	68.60
		2	Opened: s11, and s21 Closed: s71, s72, s75,s77, s78 and s79	None	0.7684	0.1711	-2	+4	0	0.9757	1.0125	29.38
		3	Opened: s11, s37, s45, s47, s64 and s64 Closed: s69, s70, s71, s74 s75,s76, s77, and s78	None	0.8679	0.1932	+8	+11	0	0.9634	1.0344	99.87

Table 3. Service Restoration with OLTC and CB at Different Load Levels

Case2: Service Restoration with OLTC and CB

System	Load Level	Scenario	Switching Operation	De-energized node	VDI	Obj.	OLTC at s/s-1	CB	Vmin [pu.]	Vmax [pu.]	Time Computation [s]
33 - Bus	100%	1	Closed : s33, and s36	None	0.0067	0.1589	+10	8	0.9817	1.0313	2.61
		2	Closed: s34, s35, and s37	None	0.0080	0.1623	+12	8	0.9874	1.0375	6.03
	130%	1	Closed: s33, and s36	None	0.0166	0.1611	+15	8	0.9743	1.0469	4.69
		2	Closed: s35, s36, and s37	None	0.0253	0.2079	+16	8	0.9671	1.05	6.12

System	Load Level	Scenario	Switching Operation	De-energized node	VDI	Obj.	OLTC at s/s-1	OLTC at s/s-2	CB	Vmin [pu.]	Vmax [pu.]	Time Computation [s]
70 - Bus	100%	1	Opened: s31 Closed : s71, s75 and s78	None	1.7565	0.5193	+11	0	5	0.9527	1.0344	25.76
		2	Opened: s33 Closed: s69, s71, s73, s78 and s79	None	0.5690	0.1682	0	0	7	0.9774	1.0099	4.37
		3	Opened: s7 Closed: s69, s73, s77, s78 and s79	None	1.0524	0.3112	+13	0	7	0.9620	1.0406	21.23
	130%	1	Opened: s11 Closed: s69, s78 and s79	None	1.9616	0.4367	+12	0	3	0.9501	1.0375	15.91
		2	Opened:s37 Closed: s69, s70, s73, s78 and s79	None	1.7460	0.3887	-3	0	7	0.9501	1.0000	18.67
		3	Opened: s6 and s29 Closed: s71,s73, s75, s77, s78 and s79	None	1.4457	0.3219	+12	0	1	0.9563	1.0375	59.11

5. CONCLUSIONS

This paper presented a novel Improved Sequential Opening Branch (ISOB) algorithm to the problem of service restoration method, to minimize the percentage of voltage deviation index in distribution systems, taking into consideration voltage control devices such as on-load tap changer (OLTC) transformer and capacitor bank (CB) in the restorative state. The results showed that the suggested method may offer solutions with higher load restored and an ideal amount of switches operating when combined with voltage control devices. Additionally, it was shown that the voltage control devices increase system voltage magnitudes to minimize de-energies nodes, allowing more effective restoration techniques. Future work, A potential way to improve the reliability indices in the following studies is to propose a method that simultaneously adjusts the optimal voltage control device and compensates for reactive power from PV smart inverter (PVSI) with other test systems validated in active distribution networks during the restorative stage.

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