Restoration of Power Distribution Networks – A Fast Evolutionary Approach based on Practical Perspectives

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ABSTRACT

The restoration of power distribution systems has a crucial role in the electric utility environment, taking into account both the pressure experienced by the operators that must choose the corrective actions to be followed in emergency restoration plans and the goals imposed by the regulatory agencies. In this sense, decision-aiding systems and self-healing networks may be good alternatives since they either perform an automated analysis of the situation, providing consistent and high-quality restoration plans, or even directly perform the restoration fast and automatically, in both cases reducing the impacts caused by network disturbances. This work proposes a new restoration strategy which is novel in the sense it deals with the problem from the operator viewpoint, without simplifications that are used in most literature works. In this proposal, a permutation based genetic algorithm is employed to restore the maximum amount of loads, in real time, without depending on a priori knowledge of the location of the fault. To validate the proposed methodology, two large real systems were tested: one with 2 substations, 5 feeders, 703 buses, and 132 switches, and; the other with 3 substations, 7 feeders, 21,633 buses, and 2,808 switches. These networks were tested considering situations of single and multiple failures. The results obtained were achieved with very low processing time (of the order of ten seconds), while compliance with all operational requirements was ensured.

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CCS CONCEPTS

•**Computer systems organization** → **Embedded systems;** *Redundancy;* Robotics; •**Networks** → Network reliability;

KEYWORDS

Restoration. Self-Healing. Smart-Grid. Optimization.

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1 INTRODUCTION

In recent years, energy companies have been investing in automation of the power distribution network. An increasing number of remotely controlled (*RC*) devices have been installed in distribution networks, which can allow to reestablish the energy delivery to consumers affected by outages in very short time. This recovery must be performed as fast as possible, in accordance with recommendations of regulatory agencies[1].

Energy recovery is performed by means of restoration procedures, whose main objective is to enable a feasible configuration of the power distribution network under contingency situations, in reduced time [7]. Due to the increasing number of maneuverable equipment, the set of reconfiguration possibilities may be high, which makes it hard to the system operator to take a decision. In this process, the maneuvers should be performed as fast as possible, and the system should keep the minimum amount of consumers disconnected. Also, some load should have reconnection priority,

[1] In Brazil, the restoration time should be lower than three minutes in order to avoid penalties, according with the Agência Nacional de Energia Elétrica - ANEEL [1].

and several system requirements must be considered in to order ensure that the new configuration is feasible. In such a scenario, the operators of the Distribution Operation Center (DOC) have been increasingly required for taking real-time decision under contingency situations. Therefore, it is necessary to use tools that can assist in the transfer of consumer sectors via remotely controlled switches. Such an action must be fast, in order to better attend the criteria established in the Electric Power Distribution Procedures in the National Electric System (*PRODIST* – Module 8 – Quality of Electric Energy) [1]. In addition, the technical constraints of the problem must be complied in order to ensure the quality of the product offered to final customers.

The evolutionary algorithms (*EA*) are optimization techniques that can deal with this type of problem, even in large networks [3]. Provided *EA* are adequately built, they can handle non-linear, combinatorial and highly constrained problems efficiently, achieving good solutions in short time.

This work presents an evolutionary algorithm to assist operators in power distribution network restoration, after faults in one or more points of the network. It applies to remotely controlled switches, in order to promote network recovery in an automated way. Differently from other literature works, it handles the faults in the same way they are reported to the DOC operators, instead of assuming that the exact location of the fault is known. The algorithm aims to minimize the number of disconnected load while guaranteeing that system constraints, such as bus voltage limit and cable current capacity, are complied. Other objectives that are usual in literature, such as the number of maneuvers performed or the time for performing the maneuvers, are not relevant in the context of this work since all the maneuvers will be performed in remotely controlled equipment. The implementation of the proposed tool may have an important role in the daily routine of the distribution utilities since it can assist the operators to improve the continuity[2] and the energy quality indices, through a more agile and reliable restoration process. The integration of the proposed system with the Supervisory Control and Data Acquisition (*SCADA*) will allow the system to be restored automatically and in real time, seeking the best configuration at the moment of the fault. Finally, the proposed computational system promotes self-healing, which makes the power distribution network closer to the concept of Smart Grids.

The paper is structured as follows: the problem statement is presented in section 2; a literature review is given in section 3; the details of the proposed algorithm are presented in section 4; some results obtained on two real systems are discussed in section 5; finally, some concluding remarks are drawn in section 6.

2 PROBLEM STATEMENT

The modification of the distribution network topology in normal operation usually aims to reduce losses [2] and it is known as network reconfiguration. The reconfiguration of the network in order to recover the system from faults is often referred as network restoration. In such a problem, the following requirements should be considered [14]:

- to restore as many loads as possible, while considering priority customers;
- to ensure compliance with operation constraints;
- to present a feasible sequence of operations that should be performed to reach the final configuration;
- to ensure load balancing;
- to be executed in short time;
- to maintain the network radial, since this structure makes it easier to perform fault location, isolation, and protection coordination.

The network restoration is a complex combinatorial optimization problem due to the large number of equipment involved and the characteristics of the distribution system (nonlinear and highly constrained). This problem can demand a long optimization time to reach feasible solutions.

In practice, the operators of the control rooms use their expertise and previously elaborated contingency plans to assist in system restoration. In general, this process leads to high reestablishment times, which implies in payment of fines and financial compensation by the energy utilities. For this reason, this topic has received more attention from researchers in recent years [5, 8, 12, 13].

It is often assumed that the protection of the primary distribution system is properly coordinated. It means the occurrence of a fault implies the actuation of the closest protection device upstream to the fault location. All algorithms described in the literature consider the sector (*or sectors*) in which the fault occurred as being known. In real life, operation technicians receive fault occurrence notice by three ways: (*i*) equipments equipped with fault current sensor and communication interface; (*ii*) consumer calls to the utility call center, or; (*iii*) information provided by work teams sent to the field in order to identify the precise location of the fault. In cases (*i*) and (*ii*), which are the first informations to arrive, the operator cannot identify the precise location of the fault, but she/he can estimate a region in which it necessarily occurred, due to protection coordination assumption. Therefore, the knowledge of the faulty point is not a valid premise from the practical perspective.

In the proposed algorithm, the faulty sectors are determined through the identification of the protection equipment that operated. Such an information is usually obtained in real time, from the SCADA. Once the operator is informed of protection equipment actuation, she/he should immediately start to perform the restoration maneuvers. If these maneuvers are performed in very short time, it is possible to reduce the payment of fines and compensations by the distribution utility, since part of disconnected clients would be restored within the tolerance time defined by the regulation agency. It should be emphasized that this procedure does not restrict the disconnected area to the smallest number of sectors possible, since all sections between the operated protection device and the other protection devices downstream must be considered as "in fault". However, given the information available shortly after the fault occurrence, this is the smallest area that can be specified as the one that surely contains the fault. In addition, once the fault location is better identified, it is possible to transfer the other disconnected sectors in a second restoration step.

[2]The indices DEC, DIC and DMIC are defined by the Brazilian regulation agency in order to measure the duration of energy interruptions.

2.1 Mathematical Formulation

The distribution network restoration was modeled as the single-objective optimization problem of minimizing the percentage of disconnected loads, as shown in Equation 1.

$$\min \left\{ \frac{N_U}{N_L} \times 100\% \right\} \tag{1}$$

The following constraints should be attended:

C1: Current capacity on system equipments (cables, switches, voltage regulators, among others) – Equation 2:

$$I_i \leq I_i^{cap} \cdot \left(1 + \frac{F^{overload}}{100} \right) \tag{2}$$

C2: Maximum current due to protection adjustment – Equation 3:

$$I_j \leq k \cdot I_j^{prot} \quad , \quad k < 1 \tag{3}$$

C3: Minimum and maximum voltages in load buses – Equation 4:

$$V^{min} \leq |V_j| \leq V_j^{max} \tag{4}$$

C4: Radiality.

in which:
N_U: number of disconnected loads after application of restoration plan;
N_L: number of disconnected loads just after the outage;
I_i: current on branch i;
I_i^{cap}: current capacity of branch i;
$F^{overload}$: permissible overload factor (in %);
I_j^{prot}: trigger current[3] of the protective device j;
V^{min}: minimum acceptable voltage (in p.u.);
V^{max}: maximum acceptable voltage (in p.u);
V_j: voltage in load bus j.

The percentage of disconnected loads refers only to loads within healthy sectors (sectors without failures). This means that it is possible to achieve 0% of disconnected loads. However, such a restoration level may be not reachable in some cases due to two possible situations: (i) sometimes there are no routes between the active part of the system and a potentially restorable sector, or; (ii) even if a route exists, in some cases it cannot be used because the corresponding solution violates some of the problem constraints (C1 to C4).

3 LITERATURE REVIEW

The state of the art methods used to handle distribution system restoration comprise deterministic greedy heuristics, implicit enumeration algorithms and metaheuristic/computational intelligence methods [3].

Deterministic greedy heuristics are constructed based on the specific problem characteristics. These methods are commonly single-objective, and the objective is always minimized in a heuristic way, which often leads to a local optimum. The main advantage of those methods is that they can be built in order to consume a low computational effort. Some examples of works that employ this class of methods can be seen in [4, 9].

[3]Current in which the protection device opens.

In implicit enumeration approaches, the restoration problem is modeled as an integer optimization problem, which is solved using some exact method, such as dynamic programming, branch-and-bound, cutting planes, and so on. The optimization algorithms employed in those cases often have exponential or factorial worst case complexity, which makes them unsuitable for dealing with large systems. Examples of approaches that use such a class of methods can be seen in [6, 10].

Finally, metaheuristic methods are a recent trend on handling restoration problems. These methods often lead to solutions that are better than the ones achieved by heuristic methods. In addition, it is possible to control their run time, performing a trade-off between solution quality and run time that cannot be made for enumeration methods. Examples of approaches within this class can be seen in [3, 11].

All the above works, along with several others in the literature, share a common drawback: they assume that exact locations of faults are available as inputs for the restoration algorithm. As mentioned previously, this assumption leads to inefficient approaches, since the determination of the fault location may take a long time, time in which load transfers could have been performed by means of remotely controlled devices. In addition, previous approaches often model the different equipment employed in network protection and maneuverability (fuse switches, reclosers, SF6 switches, voltage regulators, etc) as simple maneuverable switches, disregarding the specific characteristics of each one. The algorithm proposed here aims to enable immediate load transfers without relying on the knowledge of the exact fault location. It also considers the characteristics of each equipment installed in the network. Such a tool fits into the Self-Healing paradigm, which has been considered one of the key points of Smart Grids.

The restoration algorithm proposed in [3] was used as the foundation for the method proposed in this work. The choice for this algorithm is justified by the good results achieved by this method in large real networks.

4 THE PROPOSED ALGORITHM

The proposed algorithm, whose flow is shown in Figure 1, introduces a new fault processing methodology, which uses data from the SCADA system to identify faulty sectors in real time. Initially, the whole network is loaded from the distribution utility databases. Then, the reduction processes are employed to remove information that is not considered by the optimization algorithm in the final process step, such as non-maneuverable branches and equipments that cannot be controlled directly from the DOC. Further, based on the protection devices activated to isolate the fault, the algorithm identifies the smallest protection sectors that necessarily contain the faults and the sectors that could be restored without risk. Finally, the optimization machinery is employed to perform the restoration considering only remotely controlled switches. A brief description of each part of the method is given in the next subsections.

4.1 Reduction Process - Equivalent Systems

A complete distribution system is composed by sectors interconnected by maneuverable and non-maneuverable branches. The

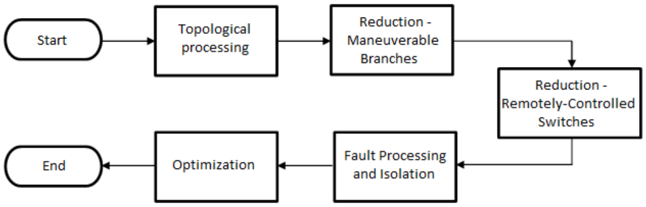

Figure 1: Proposed architecture flowchart.

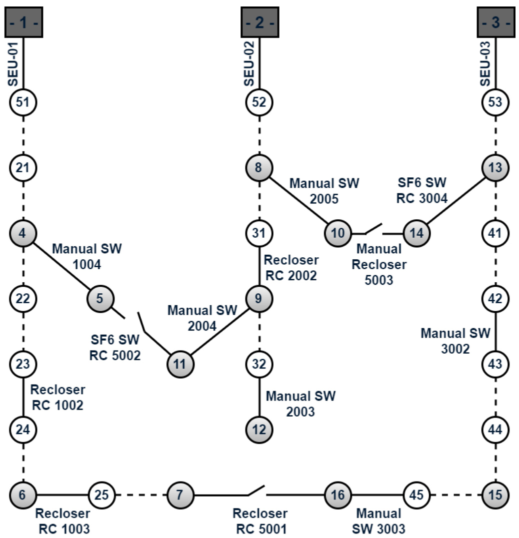

Figure 2: Complete System.

loads are grouped into sectors. A set of sectors between maneuverable branches *(lines with switches)* can be denominated load sector. An instance of a distribution system is shown in Figure 2. This system presents one substation with three feeders. The rectangles represent the sources of these feeders, while the circles represent the buses. Dashed lines are non-maneuverable branches and continuous lines are maneuverable branches *Normally Closed* (NC). Maneuverable branches *Normally Open* (NO) are represented by disconnected continuous lines.

The buses interconnected by non-maneuverable branches are grouped into load sectors in order to remove unnecessary information for the restoration problem. In this way, the equivalent system obtained is composed by load sectors interconnected only by maneuverable equipment, such as shown in Figure 3.

Since the switches can be of local (*non remotely controlled*) or remote (*remotely controlled*) operation, a further reduction is made. In this new representation, the manually operated switches are grouped, forming new load sectors. In this new reduced system, a sector is the minimum unit of the restoration problem, and it is not possible to disconnect or reconnect parts of this sector remotely. However, by sending teams to the field, a sector can be eventually divided, provided it has manual switches inside. Figure 3 shows the system after reduction.

An upper bound for the number of candidate solutions of the restoration problem can be calculated by 2^N, in which N is the

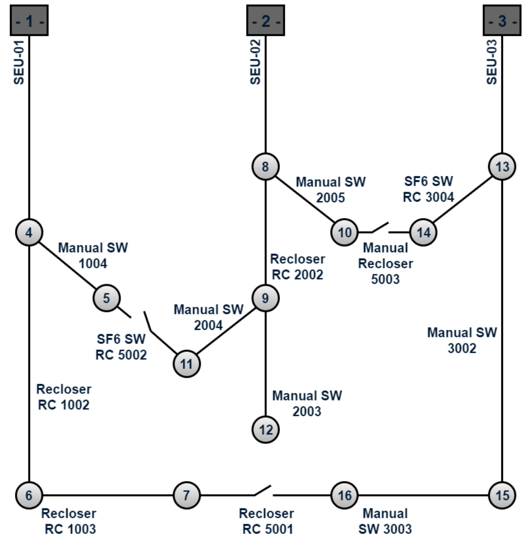

Figure 3: Equivalent System - 16 Sectors - Maneuverable Branches.

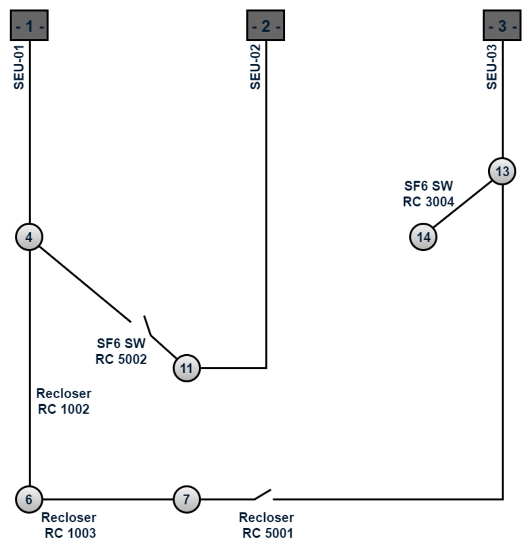

Figure 4: Equivalent System - Maneuverable equipment.

number of maneuverable equipment installed in the network. In the original configuration (Figure 2), the system is composed of 31 buses and 31 branches. After the first reduction (Figure 3), it is reduced to 16 buses and 16 branches, which implies in 65,536 possible switch combinations. Finally, after the second reduction (Figure 4), the network is simplified to 9 buses and 8 branches, resulting in only 256 possible solutions. Therefore, the reduction procedures drastically reduce the number of possible combinations, especially in the cases in which the number of remotely controlled devices is significantly smaller than the total number of maneuverable devices. With fewer combinations, it is reasonable to assume that the optimization algorithm can achieve good solutions in shorter time. This is a key feature for the restoration problem since it relies heavily on execution speed to minimize the time in which the consumers remain disconnected.

4.2 Fault Processing and Isolation

The occurrence of a fault implies the opening of the protection device immediately upstream to the faulty sector. Since each active part of the system is assumed to be a tree (*radial feeders*), such a fault does not imply the disconnection of the faulty sector only, but all sectors that are downstream to it on the topology become out of service too. The faulty sectors can be restored only after the correction of the problem. However, some disconnected sectors, which are not in fault, could be reestablished before the maintenance.

When a fault occurs, the DOC operator receives a notification in SCADA that a protection device activated. Such an information is provided to SCADA by one of two ways:

(1) If the protection device has a communication module, it sends an information to SCADA that it activated. Details about fault current module and direction can be also provided.
(2) If the protection device does not contain a communication module, its identification is performed based on client calls and informations provided by maneuverable switches that contain fault current sense and communication modules (such as SF6 switches). If two or more clients from different sectors of the same feeder notify the call center they are disconnected, it is very reasonable to assume that the fault is upstream to them. In addition, if a maneuverable device contains fault current sense and communication modules, it can be consulted to identify if the fault occurred upstream or downstream to it. All this data is combined to indicate the protection device that most likely opened. Such a device is the one that is upstream to all disconnected sectors[4], but it is also the one that is the closest to them, i.e. there is no other protection device between it and the disconnected sectors. Obviously, this process is slower than the case in which the protection device automatically notifies its opening to SCADA.

Once the protection device that opened is identified, it is necessary to reduce the region in which the fault is contained as much as possible. Such a non-restorable region is the one contained between the protection device that opened and the ones that are located immediately downstream to it (protection sector). Eventually, this region can be even reduced if fault detection information from maneuverable switches containing fault current sense and communication modules are available.

The proposed algorithm performs all these operations automatically, which is a novel contribution of this method. This procedure reduces the disconnection time experienced by the client in the recovered sectors. As a consequence, it reduces the amount to be paid in fines and financial compensations, according to regulatory rules [1].

It is important to emphasize that the proposed fault isolation method does not exclude the cases in which the exact fault location is known (after inspection or during a scheduled maintenance) because the same optimization algorithm can be executed again, with such an information.

An example of the proposed method is given. Assume that a fault occurred at sector 51. The DOC operator will be notified that protection device SEU-01 opened, disconnecting feeder 1. This means that the load sectors 4, 5, 6 and 7, as well as the sectors 51, 21, 22, 23, 24 and 25 are disconnected. The fault isolation procedure will automatically identify that the fault necessarily occurred between SEU-01 and RC 1002, since RC 1002 is the first protection device downstream to SEU-01 and there are no SF6 switches between these devices. On the one hand, sectors inside such a region could not be reconnected until the fault is isolated in its exact location or it is fixed. On the other hand, load sectors 6 and 7 could be transferred to another feeder in order to reconnect them as fast as possible.

4.3 Optimization

The fault isolation module identifies the sectors that could be recovered and the ones that should remain disconnected during restoration process. Starting from such an information, a Genetic Algorithm is employed to build the restoration plan. This algorithm works through the following steps:

(1) Generate the initial population at random and save it as $\mathcal{P}$;
(2) While the stop criterion is not met:
    (a) Perform reproduction selection in $\mathcal{P}$ and save it as Q;
    (b) Perform crossover, mutation, and local search in Q and save it as Q;
    (c) Perform survival selection in $\mathcal{P} \cup Q$ and save it as $\mathcal{P}$;
(3) Return the best solution from $\mathcal{P}$.

This algorithm and the one proposed in [3] share several features, such as representation scheme, decoding, incremental evaluation, crossover, mutation, and local search procedures. The objective function and the selection procedures are the main differences between the two methods. In [3], two objective functions are considered: (*i*) to minimize the unrestored load; (*ii*) to minimize the restoration time. On the one hand, the first objective function is the same considered here (see subsection 2.1). On the other hand, the second objective does not make sense in this work, because all maneuvers are performed in remotely controlled switches, i.e. they can be performed almost instantaneously. However, assume that two different solutions lead to the same restoration level, but one of them requires less maneuvers to reach such a level. In this case, such a smaller solution would be preferable for two reasons: (*i*) less maneuvers tend to imply in less changes in network operation conditions; (*ii*) the number of maneuvers necessary to return the system back to the initial topology is lower in this case. Due to these aspects, we adopted the number of maneuvers as an auxiliary criterion to choose between solutions with the same restoration level. Finally, if two solutions restore the same amount of loads and spend the same number of maneuvers, the choice between them is made based on the area under the curve unrestored loads × number of maneuvers, which represents a proxy of the undelivered energy during the execution of the restoration procedure. Therefore, the solutions are lexicographically ordered by the algorithm considering the following rule set:

(1) Choose the solution with better restoration level.

[4]The information that a sector is disconnected is provided by the users through calls to the call center.

(2) If the two solutions have the same restoration level, then choose the one that demands less maneuvers.
(3) If the two solutions have the same restoration level and demand the same number of maneuvers, then choose the one with lower area under the curve unrestored load × number of maneuvers.

Since the proposed algorithm is single-objective, it does not employ the same adapted SPEA2 selection scheme proposed in [3]. Instead, selection procedures are performed as follows:

Reproduction selection: binary tournaments are performed on population $\mathcal{P}$, until N_i individuals are selected for composing Q (both populations have the same size). The solutions on each tournament are compared using the rules 1, 2, and 3, described above.

Survival selection: the solutions in $\mathcal{P} \cup Q$ are lexicographically ordered and the best N_I solutions are chosen to compose population $\mathcal{P}$ (elitism).

Such as discussed above, the remaining features and operators of the algorithm are exactly the same ones employed in [3]. They are not presented here for sake of brevity. For additional information, please refer to the original reference.

5 RESULTS

To validate the proposed methodology, three failure scenarios were tested, considering single and multiple failures. These scenarios are discussed bellow. The simulations were performed using Matlab R2012a in an Intel(R) Core(TM) i7-3630QM CPU @ 2.40GHz, 6GB RAM, and Windows 10 Home Single Language.

The proposed algorithm was applied to real systems from a Brazilian Distribution utility. The system A contains 5 feeders, 703 buses, and 132 switches, with 15 ones remotely controlled. The system B contains 7 feeders, 21,633 buses, and 2,808 switches, in which 40 are remotely controlled. The algorithm was executed 20 times in each case. In the examples considered here, the loads were estimated based on the expected consumption at the peak hours on a weekday. The exact parameters of the system are not provided here due to a confidentiality agreement.

5.1 Scenario A - System A - Single Failure

The equivalent System A, considering only remotely controlled switches, is shown in Figure 5. The sectors 1, 16, 9, 13, and 15 are feeders and they were named AL-01 to AL-05 for simplicity. It is important to note that the ordering of the sectors in the figure is not related to their positions in the field. They are represented in a hierarchic structure in order to facilitate visualization.

In the first scenario, it was considered a fault in sector 2, which forced the actuation of the protection device at the output of the feeder AL-01, (see Figure 6). It is important to remark that the opening of AL-01 is the only information noticed by the DOC operator and, consequently, the only information provided to the restoration algorithm. In practice, this type of fault is called distribution line blocking, being very common in the system operation. With the blocking of the feeder AL-01, all loads in that distribution line are interrupted: sectors 2, 4, 6 and 7. Since the protection is coordinated, the fault must be located between the operated protection and the reclosers 150008 and 8628.

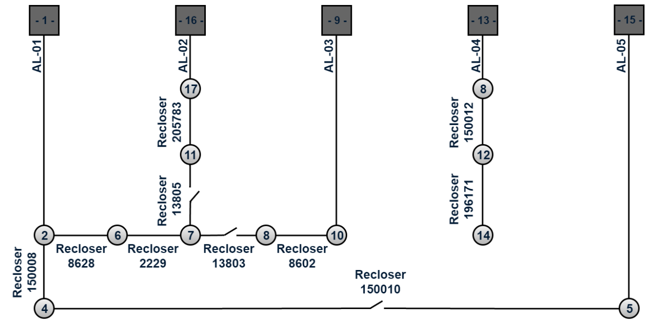

Figure 5: System A.

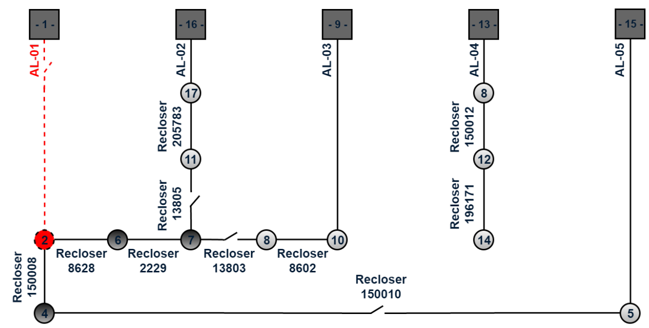

Figure 6: System A – Scenario A.
In this figure: red circle: failed; light gray circle: normal; dark gray circle: disconnected; black continuous lines: closed devices; disconnected black continuous lines: opened devices; red dashed lines: activated protection device.

The algorithm returned the following sequence of maneuvers:

(1) open recloser 8628;
(2) close recloser 13803;
(3) open recloser 150008;
(4) close recloser 150010.

In the first stage, steps 1 and 2 recovered approximately 72% of the disconnected loads. In the following stage, steps 3 and 4 (totaling four maneuvers), reduced to 0% the unrestored loads. It is noteworthy that, in this case, the stages could be inverted with the same final result. However, the sequence obtained by the restoration tool presented is more interesting from a practical viewpoint, since it recovers the largest sector of loads at first. Figure 7 shows the final configuration of the restoration process, after execution of the two stages of the solution.

5.2 Scenario B - System A - Multiple Failures

In the second scenario, three simultaneous failures were simulated: faults at sectors 2, 4, and 10, that caused the operation of protection devices in AL-01, in AL-03, and recloser 150008. In response, the proposed algorithm returned the following sequence of maneuvers:

(1) open recloser 8628;
(2) close recloser 13805.

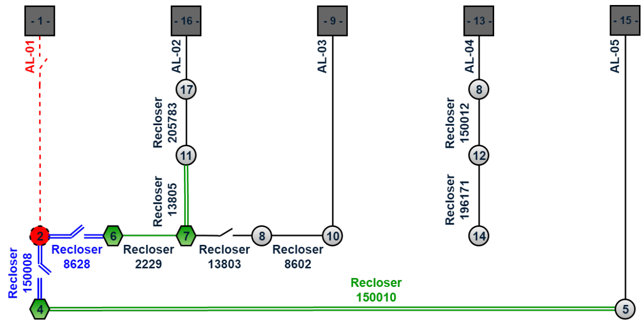

Figure 7: System A – Scenario A: Network after restoration. In this figure: double line: maneuvered devices; green hexagon: sector restored.

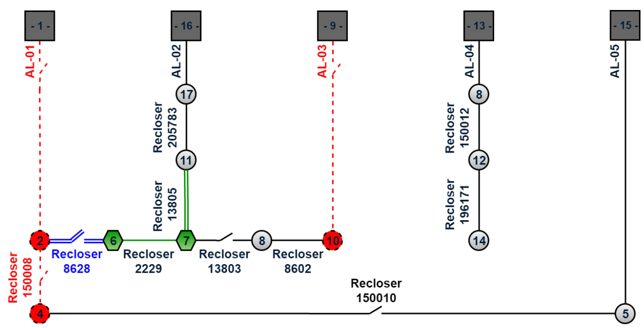

Figure 8: System A – Scenario B: Network after restoration.

Such a solution (see Figure 8) found is composed of only one stage, restoring 61% of the disconnected loads. Although, by topological considerations only, reclosers 13803 (to close) and 8602 (to open) could be used to restore sector 8, this was not possible in practice because this alternative violates current capacity of cables in feeder AL-02. Therefore, sector 8 had to remain disconnected.

5.3 Scenario C - System B - Multiple Failures

Five failures were simulated in the third scenario, such as shown in Figure 9. This is a critical situation since AL-02, AL-05, and AL-06 feeders are completely blocked. In this case, the disconnected loads of the AL-06 feeder as well as of 216055 and 32900 reclosers are not restorable, because there are not *NO* remotely controlled switches to transfer loads.

After simulations, the algorithm returned the following sequence of maneuvers:

(1) open recloser 154543;
(2) close recloser 295025;
(3) open recloser 137174;
(4) close recloser 222885.

This sequence of maneuvers is illustrated in Figure 9. In the first stage, 31% of the disconnected loads are recovered, through the transfer of sectors 24, 41 and 42. Sectors 6, 7 and 9, which represent 8% of the interrupted loads, are restored in the second stage, remaining disconnected 61%.

It is not possible to restore all the disconnected sectors due to current and voltage constraints in the AL-03 feeder. The largest number of restorable loads, respecting system constraints, is verified to be the one obtained by the algorithm.

5.4 Result Summary

The proposed algorithm obtained interesting results for all systems and situations tested. For the System A, the algorithm reached solutions in less than 5 seconds for both scenarios A and B. For the System B, only 10 seconds were spent. These processing times are irrelevant when compared to the maximum time established by regulatory agencies, which is 3 minutes in Brazil. Therefore, the distribution utility will not have to pay fines and compensations for the restored loads, which reduces its operational cost. It is also important to emphasize that the algorithm was executed 20 times in each one of the scenarios, and the same best solutions were found in every run. This shows the convergence ability of the algorithm.

The reader should notice that, after the execution of the restoration plan which is delivered by the proposed method, there still remain several maneuverable switches that are manually operated, which can be used to further enhance the restoration level. It would be possible to perform a global optimization considering all maneuverable switches at once (the remotely controlled ones and the manually operated ones), such as proposed in [3]. However, such an approach would require computation times of several minutes for large systems, such as System B[5]. It would incur in the payment of fines regarding all disconnected loads, including the ones that could be restored within the three minute deadline.

Based on this characteristic, we suggest the following procedure: (*i*) in first place, run the algorithm proposed here, and perform the initial restoration that can be executed remotely; (*ii*) taking the solution of the first step as the initial condition to the algorithm described in [3], perform the computation of a further restoration plan, considering all switches (remotely controlled and manual) as maneuverable. A naive analysis could suggest the solution that results from steps (*i*) and (*ii*) could be sub-optimal, but it is not true. Since the maneuvers on step (*i*) are performed on remotely controlled switches only, they can be easily reversed at step (*ii*), at "zero time cost". Therefore, the algorithm in (*ii*) can achieve the global optimum without restrictions, since, in the worst case, it could reverse the system back to the initial configuration. In addition, the sectors recovered at step (*i*) are considered as healthy in step (*ii*), which reduces the cardinality of the set of feasible solutions to the problem [3]. It means that the algorithm in [3] will require less time to deliver a solution.

6 CONCLUSIONS

The requirement of compliance with targets for continuity indicators, on the distribution utility side, and the pressure to which control room operators are exposed, in a contingency situation, require the development of tools that can help decision-making in real-time network restoration.

A new methodology for real-time system restoration was presented in this manuscript. It uses remotely controlled devices to

[5]System B supplies five small and medium sized cities, with approximately 400,000 consumers.

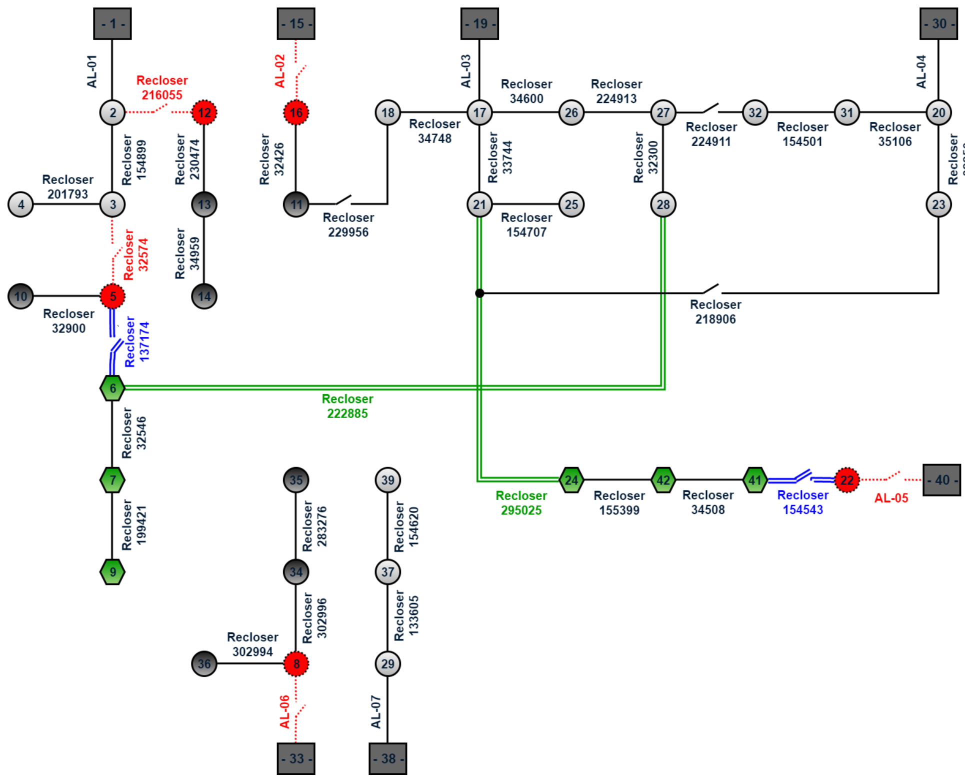

Figure 9: System B – Scenario C: Network after restoration.

perform self-healing, and the information about the exact location of the fault is not required. Two real systems were used to validate the proposed tool. The System A, with 2 substations, 5 feeders, 703 buses and 132 switches, and the System B, with 3 substations, 7 feeders, 21,633 buses and 2,808 switches, were submitted to the operation of single and multiple protection devices. Although all the remotely controlled devices present in the available systems are reclosers, the algorithm was developed for any type of equipment, such as SF6 switches, sectionalizers, among others. In all simulations, the algorithm generated the expected solutions in less than 10 seconds and repeated the results over 20 runs. The results obtained showed the efficiency of the strategy presented here.

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