A METHODOLOGY TO ALLOCATE AUTOMATIC RECLOSERS IN LARGE POWER DISTRIBUTION NETWORKS

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ABSTRACT

This paper describes the development of a methodology of optimal allocation of reclosers to improve the quality of service indices of power distribution networks. Normally Opened devices (NOs) used for distress between feeders, as well as Normally Closed devices (NCs), used in the sectioning of feeders and in the isolation of faults, are treated by the proposed approach. The methodology was implemented in a software that allows one to consider simultaneously several distribution feeders. It also allows the evaluation of the gains of load transfers and the calculation of typical quality of service indices such as SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index) and ENS (Energy Not Supplied). The validation was successfully carried out in a real case study of the EDP BANDEIRANTE distribution network, applied to georeferenced networks, with a high number of buses and line segments.

INTRODUCTION

There are several published works with the objective of allocating recloser devices such as [1], [2], [3] and [4], among others. In these works, normally the candidate positions for the installation of the sectioning device are initially selected. Then, an optimization process is performed that seeks to determine the best alternative, which combines the different positions, for the installation of the equipment. The limitations of this approach are derived from the number of candidate positions for the installation of devices, which increases significantly in real georeferenced networks. Due to their combinatorial nature, the allocation of reclosers becomes a very complex problem, and these typical approaches are limited only to the application of search techniques in networks with limited number of buses.

The present paper describes a methodology and computational application developed and applied in real distribution networks, with tens of thousands of buses, to define optimal alternatives for the installation of reclosers, indicating the amount of equipment and the sectioning positions, to provide the improvement in terms of the quality of service and respect the total number of equipment available.

An important advance to be highlighted was the consideration in the methodology not only of NC equipment, but also the allocation of NO remote-controlled devices between circuits. Such equipment, in practice reclosers, can provide relief to network segments with many consumers, contributing to the reduction of continuity indicators.

The development was carried out through a project of the R&D program of ANEEL (National Electric Energy Agency), with EDP (*Energias de Portugal*) as proponent and NAPREI (Support Centre of Research in Smart Grids) of USP (University of Sao Paulo) as executor.

DEVELOPMENT

Methodology

The methodology proposed in this project and presented in this paper was divided into three stages. The first of these consists of enumerating possible positions for the installation of Normally Opened Automatic Reclosers (RA-NO) between the feeders of the distribution network being evaluated. These positions are suggested by rules based on the distribution of loads, or determined by the user based on their experience. At first, all positions where some type of installed switch already exists (such as regular switches, fuses, etc.) are candidate positions for the installation of automatic reclosers. However, heuristics have been developed to ensure certain logic in the determination of candidate positions throughout the evaluation, for example, it is not possible to install automatic reclosers after a fuse.

The second step consists of enumerating configurations for the installation of Normally Closed Automatic Reclosers (RA-NC) in each feeder of the distribution network under study, to promote improvement in quality service indices. The possible configurations are determined by the maximum number of remote reclosers to be installed in each feeder. The maximum number of reclosers is defined initially by the simulations, which identify when the cost of deploying an additional recloser exceeds the amount of ENS avoided through its installation.

The third and final stage consists in selecting the best configuration for the RA-NC allocation to be applied to each feeder, considering a fixed combination of RA-NO allocation to be applied to the entire distribution network under evaluation. At this stage, one seeks to maximize the improvement of a merit index that includes, in a weighted way, collective indices of quality of service.

In the second and third stages, the optimization technique known as Genetic Algorithms (GA) was used.

Step 1 - State Enumeration - NO Recloser Allocation

The first step consists in enumerating configurations for the installation of RA-NO between the feeders in the distribution network being evaluated. At first, the planner engineer indicates the possible positions for installation of RA-NO. NO switches already present in the network are automatically considered as candidate positions for installing RA-NO.

Each of these configurations corresponds to a distribution network state. Each state is responsible for a distribution network response to the various contingency possibilities that may occur in it. That is, the possibilities of reconfiguration of the network during contingencies will depend on the number of RA-NO, due to the different feasible transfer possibilities. Therefore, the distribution network response for a given contingency will depend on the number of RA-NO considered and their positions (ie, the state of the distribution network).

Step 2 - Configuration Enumeration for NC Recloser Allocation

The second step consists of enumerating configurations for the installation of RA-NC. In this step, the optimum position for the installation of only one RA-NC, or the optimum positions for the installation of a set of RA-NC in each feeder of the distribution network being evaluated, is determined. The maximum number of RA-NC to be installed simultaneously is determined a priori for the execution of this step.

The proposition of candidate positions for the installation of RA-NC is done automatically by the system. Determining the optimal position for installation of only one RA-NC or optimum positions for the simultaneous installation of a set of RA-NC are different optimization problems. Therefore, several optimization problems are solved in this step, one for each number of RA-NC to be allocated (a problem for allocating only one NF recloser, another problem for allocating two NF reclosers, and so on). Each optimization problem corresponds to the determination of an alternative for the installation of RA-NC, and consequently, an alternative to the configuration of the distribution network.

Step 3 - Global Optimization

As described, the previous steps list the optimal configurations for the installation of reclosers in each state of a feeder, to improve the performance quality of service indices. It is necessary to determine which of the configurations determined for each feeder should in fact be applied to maximize the improvement in the overall indices of the distribution network and respect the amount of equipment available. At the same time, it should be determined which states will be applied to each feeder in the distribution network being evaluated, knowing that RA-NO affect two feeders simultaneously. Therefore, the third step of the proposed methodology describes how the choice of possible configurations for each feeder can be made using the GA-based technique. In GAs, possible solution alternatives to the problem are encoded by a string. Then, initially, several solution alternatives are encoded in the corresponding strings, which initiate the iterative process of GAs. In the iterative process, they undergo modifications, giving rise to more interesting solution alternatives to the problem, in a manner analogous to the process of natural evolution.

The coding for the proposed solution alternatives was illustrated in Figure 4. Two types of positions in the string can be seen. The binary positions at the beginning of the string correspond to the RA-NO. They determine the installation (unit value) or not (null value) of a RA-NO.

RA-NOs				Feeders					
#1	#2	#3	#4	#1	#2	#3	#4	#5	#6
0	1	1	0	3	2	1	0	0	4
Optimized alternatives per feeder regarding the number of RA-NC to be allocated				0	0	0	0	0	0
				1	1	1	1	1	1
				2	2	2	2	2	2
				3	3	3		3	3
				4	4			4	4
				5					5

Figure 4 - Example of string considering optimal configurations for the distribution network under evaluation.

The integer positions in the string correspond to a specific feeder present in the distribution network being evaluated. For each position, there is a possible set of integer values, which correspond to the configurations for the installation of the reclosers determined through Step 2, previously described. Therefore, a string indicates which RA-NO should be installed and which RA-NC configurations should be applied to each feeder.

Evaluation of Solution Alternatives

In this section, just to elucidate the reader on how the evaluation of the listed configurations occur, a brief discussion of the relative aspects of the evaluation of the settings was presented. The evaluation of each configuration considers the benefits of its application and the number of reclosers considered. Generally, the evaluation can be equated by the sum of benefits ($benef_i$) provided by the application of the corresponding configurations in each feeder, normalized by the number of devices (num_dev_i). Equation (1) illustrates the evaluation process through its equation in terms of linear programming.

$$
\begin{aligned}
&minimize \sum_{i=1}^{n} \frac{num\_dev_i}{benef_i} \\
&subject\ to: \\
&\quad num\_dev_i \leq max\_num\_dev \\
&\quad max\_num\_dev \leq \frac{bud}{cost\_un}
\end{aligned}
\tag{1}
$$

Where:

- max_num_dev is the maximum number of devices to be allocated in the concession area being analyzed;
- bud the value of the budget;
- and $cost\_un$ the unit value of each device.

In a simplified way, the benefit can be obtained by calculating the quality of service indices for the network configuration under analysis. Through the proposal made in this paper, the impact of a recloser configuration on the collective indicators was considered considering the following indices:

- CI: Total Frequency of Interruption per Consumer Unit;
- CIH: Total Duration of Interruption per Consumer Unit;
- ENS: Energy not supplied due to occurrences of Interruptions.

Total Frequency of Interruption

If NC_i is the number of clients that had their supply interrupted in the contingency i occurred during the period of observation, one may calculate the total frequency of interruption as illustrated in Equation (2):

$$CI = \sum_i NC_i \tag{2}$$

Through this approach, it is avoided that the weighting by the total number of consumers of each feeder distorts the calculated values, as it happens with the regular SAIFI equation.

Total Duration of Interruption

If Dur_i is the average duration of the contingency i, usually measured in hours, and counted from 3 minutes (minimum duration for an interruption in Brazil), one may calculate the total duration of interruption as illustrated in Equation (3):

$$CIH = \sum_i (NC_i \times Dur_i) \tag{3}$$

Through this approach, it is avoided that the weighting by the total number of consumers of each feeder distorts the calculated values, as it happens with the regular SAIDI equation.

ENS index

The methodology also considers the ENS equation. The ENS can be defined as the sum of the product between the average demand not supplied due to interruptions in power supply, D_i^{med} and the respective durations for each load block i, Dur_i, as illustrated by Equation (4):

$$ENS = \sum_i \left(D_i^{med} \times Dur_i\right) \tag{4}$$

The average demand is obtained by the relation between the monthly consumption of each load point and the average number of hours in a month, as seen in Equation (5):

$$D_i^{med} = \frac{\varepsilon_i^{monthly}}{730} \tag{5}$$

Where $\varepsilon_i^{monthly}$ is the average energy consumed by the clients affected in interruption i in one typical month.

Definition of Objective Function

The objective function proposed through the equations presented in this section focuses on improving the quality of service. A Merit Index (MI) allows one to quantify the improvements resulting from the installation of reclosers. At first, the proposed MI was based on the difference between any evaluation grade for the initial state of the electrical network (without installation of the reclosers - $Grade_{without}$) and the same grade for the state determined by an alternative allocation (with the installation of the reclosers - $Grade_{with}$). To allow comparison with impacts on different grades, the difference is then normalized by $Grade_{without}$. Equation (6) illustrates the expected behavior for the proposed MI.

$$MI = \frac{Grade_{without} - Grade_{with}}{Grade_{without}} = 1 - \frac{Grade_{with}}{Grade_{without}} \tag{6}$$

Thus, the impact assessment in each index follows the proposed model for the determination of MI. In this evaluation, the variation of the CIH and CI and END indices is verified to define a factor that can either subsidize or penalize the power distribution companies. Then, the collective performance evaluation is synthesized through a single grade, as illustrated by Equation (7).

$$
\begin{aligned}
Grade_{with/without} = {} & f_{CIH} \times Grade^{CIH} + f_{CI} \times Grade^{CI} \\
& + f_{ENS} \times Grade^{ENS}
\end{aligned}
\tag{7}
$$

Where:

- f_{CIH}: weight for the CIH in the evaluation of collective performance;
- f_{CI}: weight for CI in the evaluation of collective

performance;

- f_{ENS}: weight for ENS in the collective performance evaluation.

Technical Restrictions

The same network can assume different performance conditions due to the occurrence of contingencies, making it practically unfeasible to verify all restrictions in the recloser allocation process.

In addition, considering the constraints may prevent interesting settings for the recloser allocation from being considered due to the breach of technical limits.

In order not to interfere in the determination of alternatives that would produce the greatest reductions in continuity indicators, the proposed methodology for the recloser allocation does not consider the verification of compliance with the technical restrictions in the definition of the quantity and locations for the installation of the devices. The compliance with technical restrictions is an aspect verified after the allocation, to guide the determination of the necessary reinforcement works to enable the attendance in contingencies, considering the new possibilities of configuration existing through the allocation of reclosers. The technical restrictions are

RESULTS

The simulations were performed considering occurrences of interruptions referring to the years of 2012, 2013, 2014 and part of 2015 (until February 19, 2015) together. Another relevant premise for the studies carried out was the consideration of reclosers already previously installed or not. That is, the studies can be divided into:

- Brown Field: when considering the effects of existing reclosers and intends to install new reclosers;
- Green Field: when the existing reclosers are disregarded and it is intended to reallocate existing reclosers and even relocate new reclosers.

Figure 7 illustrates the pilot area where the proposed methodology was applied. The pilot area for application of the methodology is composed of EDP BANDEIRANTE's BONSUCESSO and DUTRA substations. For information, it should be noted that:

i. BONSUCESSO substation is composed of 9 MT feeders, one of which is a distress feeder;
ii. DUTRA substation consists of 16 MV feeders, 2 of which are distress feeders;
iii. There are 17 reclosers installed in the feeders serviced by BONSUCESSO substation, with 4 reclosers of type NA;
iv. There are 28 reclosers installed in the feeders serviced by DUTRA substation, with 8 reclosers of type NA.
v.

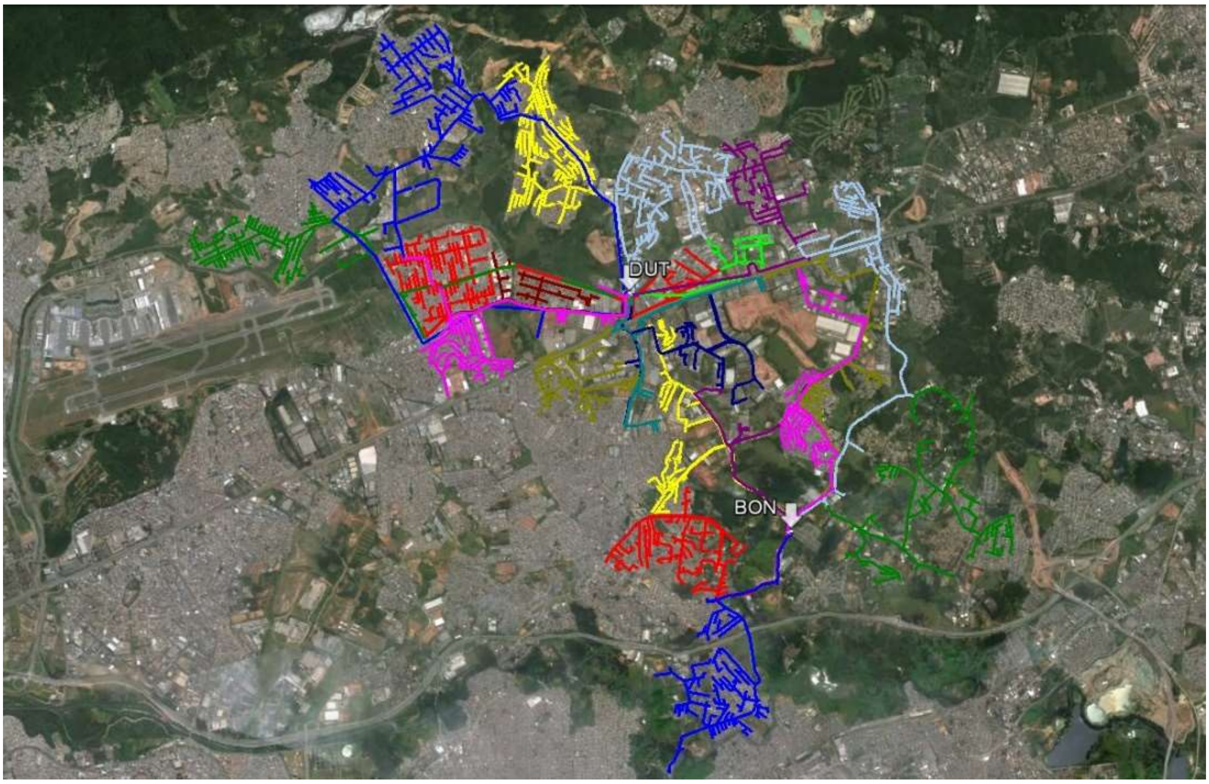

Figure 7 - Pilot area

Figure 8 illustrates the results of the simulations in a compiled way. It is possible to identify that the allocation

of new reclosers improves the quality of service performance indexes significantly (about 30% reduction). It is also noticeable that the improvement tends to be less intense with the increase of the number of devices allocated, leading to a "saturation" of the benefit from the recloser allocation (about 20% reduction for the allocation of 10 reclosers, 25% For the allocation of 20 reclosers and 30% for the allocation of 30 reclosers).
occurrences and minimum range of the reclosing function

In the case of the reallocation of the 45 reclosers in the pilot area, two simulations were made. One considering the effect of the absence of reclosers and another with the reallocation of the 45 reclosers. It is observed that the values for the quality of service indicators tend to be better than the base case, which refers to the current situation of the distribution network, where the effect of the 45 reclosers in the original positions is considered.

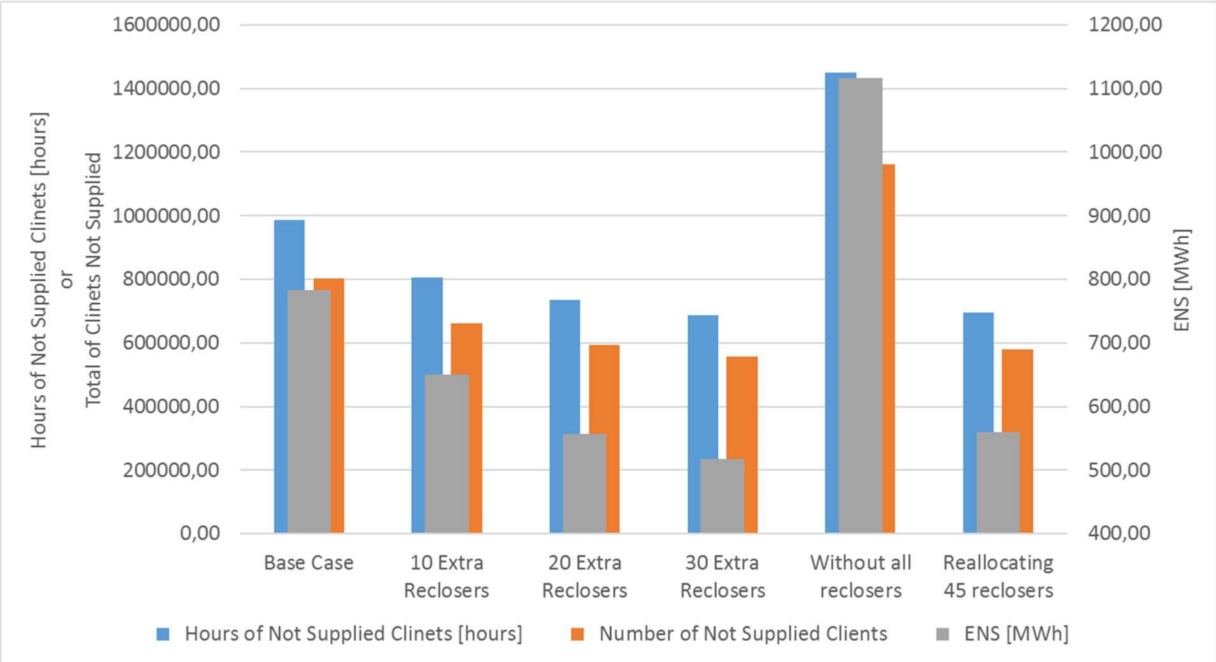

Figure 8 - Allocation of reclosers considering all

CONCLUSIONS

The methodology and its application in the EDP BANDEIRANTE network was successful, being quite broad, and can be used in distribution networks with a high number of buses. The application gives the utility a considerable gain in its continuity indicators making it quite practical and attractive. The time taken to allocate many reclosers using this methodology is significantly lower than the time spent by planners, who base their choices on the selected recloser allocations in their own experiments. The traditional selection, made by the planners, although it represents a gain in relation to the network that will incorporate these new reclosers, does not consider all the variables involved in the continuity indicators, which are used with the application of the methodology of the present article.

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