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Automatic Restoration of Power Supply in Distribution Systems by Computer-Aided Technologies

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1. Introduction

The need to improve quality and reliability of Power Systems has contributed to the advancement of research on Smart Grids and related topics. Some challenges that motivate the deployment of such researches include the increasing in energy consumption, environmental aspects, the integration of distributed and renewable generation, and new advances in computer aided technologies and automation. Smart Grids are characterized by a series of integrated technologies, methodologies and procedures for planning and operation of electrical networks. A survey of the main projects and researches related to Smart Grid is presented in (Brown, 2008).

Some of the main desired features in a Smart Grid are the low operating and maintenance costs and the ability to self-healing. In this context, utilities have concentrated significant efforts in order to improve the continuity of the supplied electrical energy, especially because of regulatory policies, besides the customer satisfaction and the improvement of the amount of energy available to commercial and industrial activities. However, supply interruptions are inevitable due to implementation of the expansion of the system, preventive maintenance on network equipment, or even by the action of protective devices due to defects.

A distribution network can have its topology changed by opening or closing switches, allowing to isolate faults and to restore the supply in contingency situations, and also in case of scheduled shutdowns. In addition, the change of topology allows a better load balancing between feeders, transferring loads of heavily loaded feeders to other feeders, thus improving the voltage levels and reducing losses and increasing levels of reliability.

The reconfiguration of a distribution network is considered an optimization problem in which the objective is to seek for one configuration, among several possible solutions, that leads to better performance, considering the ultimate goal of the reconfiguration and observing the network constraints. One factor that increases the complexity of the problem is the large number of existing switches in a real distribution network, which leads to a lot of different possible configurations to be analyzed.

The stages of planning the reconfiguration of distribution networks usually involve the collection of information of the network and load, the application of methodologies for estimating loads and calculation of power flows, and the application of the methodology for network optimization.

The behavior of the load is essential in the study of reconfiguration of distribution networks, because load variations cause demand peaks at different periods, and thus the reconfiguration at a particular period may not meet the objectives and constraints at later periods.

Several researches are related to the reconfiguration of distribution networks, based on mathematical methods, heuristics and artificial intelligence techniques, as shown in (Takur & Jaswanti, 2006). Generally, the reconfiguration aims to meet the maximal number of consumers as much as possible, or the maximum energy demand, with loss minimization and load balancing. The reduction of losses is often taken as the primary objective of the reconfiguration. When more than one objective function is defined, it is necessary to apply multicriteria methods for decision making. Among the restrictions, there is the need to maintain a radial network, and the operation within the limits of voltage and current capacity of equipment and conductors of the line. The coordination of the protection system of the new network configuration should be taken into consideration.

In recent years, new methodologies of reconfiguration of distribution networks have been presented, exploring the greater capacity and speed of computer systems, the increased availability of information and the advancement of automation, in particular, the SCADA (Supervisory Control and Data Acquisition). With the increased use of SCADA and distribution automation - through the use of switches and remote controlled equipment - the reconfiguration of distribution networks become more viable as a tool for planning and control in real time.

Act as soon as possible in a contingency situation may result in a minimum cost to the utility and consumers. When a fault is identified at any point of the network, the following procedures must be performed: identify the location of the problem; isolate the minimum portion of the distribution system by opening normally closed switches; restore the power supply to consumers outside the isolated block reclosing the feeder breaker and/or normally open switches; correct the problem; re-operate the switches to get back to the normal network status. To do that, generally a maintenance crew has to travel long distances, and may be affected by traffic jams and unfavorable accesses.

The automation of distribution systems, with the installation of remote controlled switches, plays an important role on reducing the time to implement a service restoration plan (Sperandio et al., 2007). These devices have shown to be economically viable due to the growth of a large number of automation equipment suppliers and new communication technologies.

The commitment of an efficient system to operate these devices is quite important for the utilities, aiming to guarantee the technical feasibility of the network reconfiguration with minimal time necessary to restore the energy supply of the affected consumers.

In this chapter, a methodology for the automatic restoration of power supply in distribution systems by means of remote controlled switches is presented. It includes a validation of the technical feasibility for the reconfiguration of the network in real time using computer simulations. Since there may be many configuration options with different gains, an algorithm based on a multiple criteria decision making method, the Analytic Hierarchical Process – AHP (Saaty, 1980), is employed to choose the best option for load transfers after contingencies. The AHP method has proven to be effective in solving multi-criteria problems, involving many kinds of concerns including planning, setting priorities, selecting the best choice among a number of alternatives and allocating resources. It was developed to assist in making decisions where competing or conflicting evaluation criteria difficult to make a judgment (Saaty, 1994). Additionally, the algorithms for load modeling and load flow are also presented, since they are essential for analysis of the maneuvers.

As a result, load transfers are carried out automatically, being preceded by computer simulations that indicate the switches to be operated and that ensure the technical feasibility of the maneuver, with the characteristics of agility and safety for the power restoration and in agreement with the Smart Grids concepts. The developed tool has been applied in a pilot area of a power utility in Brazil. The reduction in the displacement of maintenance teams and improving indices of continuity characterize the greatest benefits for the company, making a difference in the market and, consequently, generating economic and productivity gains.

2. Modeling of power load profiles

The most common information on power loads profile comes from utilities charges, based on measurements of monthly energy consumption. Unfortunately, these data are insufficient for the analysis of the distribution systems, since they do not reflect the daily power behavior. Therefore, a methodology for power load modeling is need, which usually employs typical load curves for their representation. A technique for building the typical load curves that has advantages in relation to the traditional statistical methods was presented in (Bernardon et al., 2008). It reduces the influence of random values and also the amount of measurements required to form a representative sample of the load types. Instead of using the simple average to determine the active and reactive power values for a typical load curve ordinate, the following equation is used:

$$X_t = \frac{1}{5} \cdot \left[2M\{X_t\} + 2Me\{X_t\} + Mo\{X_t\} \right] \quad (1)$$

where:
X_t – active (P_t) or reactive (Q_t) power value for the time t of the typical load curve;
$M\{X_t\}$ – sample average;
$Me\{X_t\}$ – sample median (central number of a sample);
$Mo\{X_t\}$ – sample mode (most frequently occurring value of a sample).

According to the monthly power consumption data and economic activity developed, each customer is associated to a typical load curve. Based on the load factor (LF) and monthly energy consumption values (W), the maximum power demand (P_{max}) for a k group of consumers is calculated:

$$P_{max_k} = \frac{W_k}{T \cdot LF_k} \tag{2}$$

The typical curves utilized are normalized in relation to the maximum active demand, and the load curve for a *k* group of consumers is built by multiplying each ordinate by this value:

$$\begin{aligned} P_{kUt} &= P_{max_k} \cdot P^*_{kUt} \\ P_{kSt} &= P_{max_k} \cdot P^*_{kSt} \\ P_{kDt} &= P_{max_k} \cdot P^*_{kDt} \end{aligned} \tag{3}$$

$$\begin{aligned} Q_{kUt} &= P_{max_k} \cdot Q^*_{kUt} \\ Q_{kSt} &= P_{max_k} \cdot Q^*_{kSt} \\ Q_{kDt} &= P_{max_k} \cdot Q^*_{kDt} \end{aligned} \tag{4}$$

where:

P^*_{kt} and Q^*_{kt} - active and reactive power values, normalized for ordinate *t* of typical curve *k*;

U, *S* and *D* – Working days, Saturdays, Sundays/holidays, respectively.

The integral load curves for Working days, Saturdays and Sundays for the distribution transformer *j* is done through the sum of the load curves of the different groups of N_k consumers connected to it:

$$P_{jUt} = \sum_{i=1}^{N_k} P_{iUt} \text{ ; } P_{jSt} = \sum_{i=1}^{N_k} P_{iSt} \text{ and } P_{jDt} = \sum_{i=1}^{N_k} P_{iDt} \tag{5}$$

$$Q_{jUt} = \sum_{i=1}^{N_k} Q_{iUt} \text{ ; } Q_{jSt} = \sum_{i=1}^{N_k} Q_{iSt} \text{ and } Q_{jDt} = \sum_{i=1}^{N_k} Q_{iDt} \tag{6}$$

Thus, it is possible to consider the load levels corresponding to the period in which the failure occurred in the distribution network. Usually, the load transfers are analyzed considering the fault's time of the occurrence and the next four consecutive hours, thus ensuring the technical feasibility of the load transfers until the network returns to its original configuration.

3. Load flow method

A version of the classical backward/forward sweep method by (Kersting & Mendive, 1976) was performed to calculate the load flow in radial distribution networks. Since the electrical loads are defined by a constant power according to the applied voltage, the circulating current varies with the voltage drops. So, the solution is found only iteratively. The resulting procedure is described as follows:

Step 1. It is considered that the voltage in all points of the feeder is the same as the voltage measured in the substation bar. This information can be automatically received by the remote measurement systems installed at the substations. Voltage drops in the branches are not taken into account in this step.

Step 2. Active and reactive components of the primary currents absorbed and/or injected in the system by the electrical elements are calculated.

Step 3. The procedure to obtain the current in all network branches consists of two stages: (a) a search in the node set is performed adding the current values in the set of branches and (b) currents from the final sections up to the substation are accumulated.

Step 4. Voltage drops in primary conductors are determined.

Step 5. From the substation bus it is possible to obtain the voltage drops accumulated at any other part of the primary network, and, consequently, the voltage values at any point.

Step 6. The difference between the new voltage values for all nodes and the previous values is checked. If this difference is small enough comparing to a previously defined threshold, the solution for the load flow calculation was found and the system is said to be convergent. Otherwise, steps 2 to 6 are repeated, using the calculated voltages to obtain the current values. The threshold of 1% was chosen, because it leads to accurate values for the status variables without requiring too much processing time.

At the end of the process, the active and reactive powers and the technical losses in the primary conductors are defined for all branches of the feeder.

This load flow method was implemented in the proposed methodology for the automatic power supply restoration. It was used for analyzing the technical feasibility of the load transfers and the results were considered as constraints in the optimization procedure. That is, such transfers may neither cause an overload on the electrical elements (conductors and transformers), nor reach the pickup threshold of the protective devices, nor exceed the limits of voltage range of the primary network. The checking of the constraints is performed by considering the load profile compatible with the period of the failure.

4. Methodology for automatic operation of remote controlled switches to restore power supply

The logic for power restoration is presented considering the hypothetical example of the simplified distribution network illustrated in Figure 1. Normally close (NC) switch and normally open (NO) switches in Figure 1 are remotely controlled. Assuming that an outage has occurred in feeder FD-1, the procedure for electric power restoration is:

- Fault downstream of NC-1 switch: in the event of this fault, the current values of short-circuit will be flagged online in the SCADA (Supervisory Control and Data Acquisition) system. So, it is assumed that the failure occurred downstream of NC-1 switch; then, this switch is operated automatically to isolate the defect.

- Fault upstream of NC-1 switch: in the event of this fault, the current values of short-circuit will not be flagged in the SCADA system. So, it is assumed that the failure occurred upstream of NC-1 switch, automatically operating the remote controlled switches to open NC-1 and to close NO-1 or NO-2 in order to transfer consumers downstream of NC-1 to another feeder.

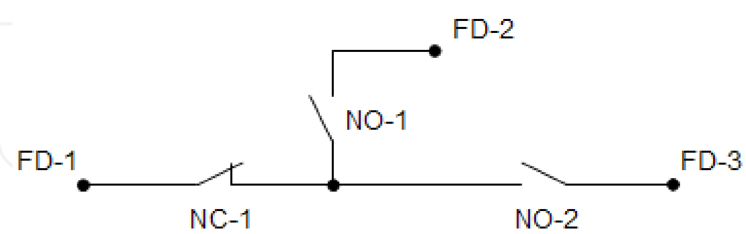

Fig. 1. Example of switches in a distribution network (FD – feeder, NC – normally closed switch, NO – normally open switch).

The technical and operational feasibility of load transfers using the remote controlled switches is verified by computer simulations. If there is more than one option of load transfer (e.g. to FD-2 or FD-3), the best option will be chosen considering the defined objective functions and constraints by a multiple criteria decision making algorithm. After this analysis, the developed tool automatically sends the necessary commands to maneuver the equipment.

Moreover, the automatic operation of remote controlled switches are carried out only after all attempts to restart the protection devices have been tried, i.e., they are done only in case of permanent fault, after a maximum of 3 minutes needed to complete the computer simulations and maneuvers of the switches since the instant of the fault identification. Figure 2 illustrates the architecture of the proposed system.

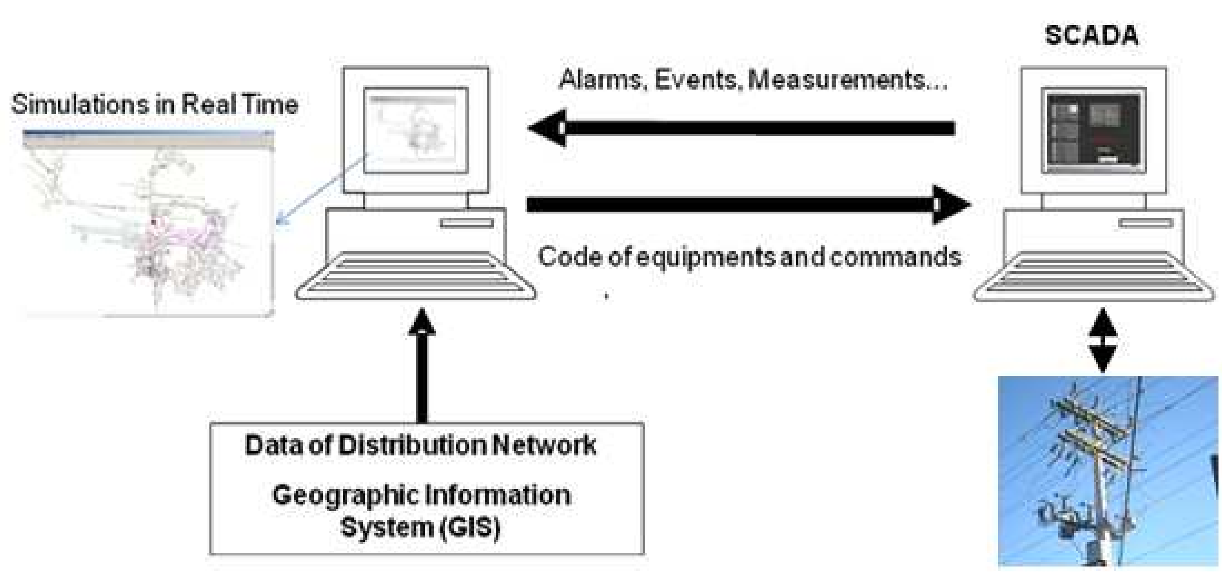

Fig. 2. Architecture of the developed system.

The flowchart of the proposed methodology is shown in Figure 3.

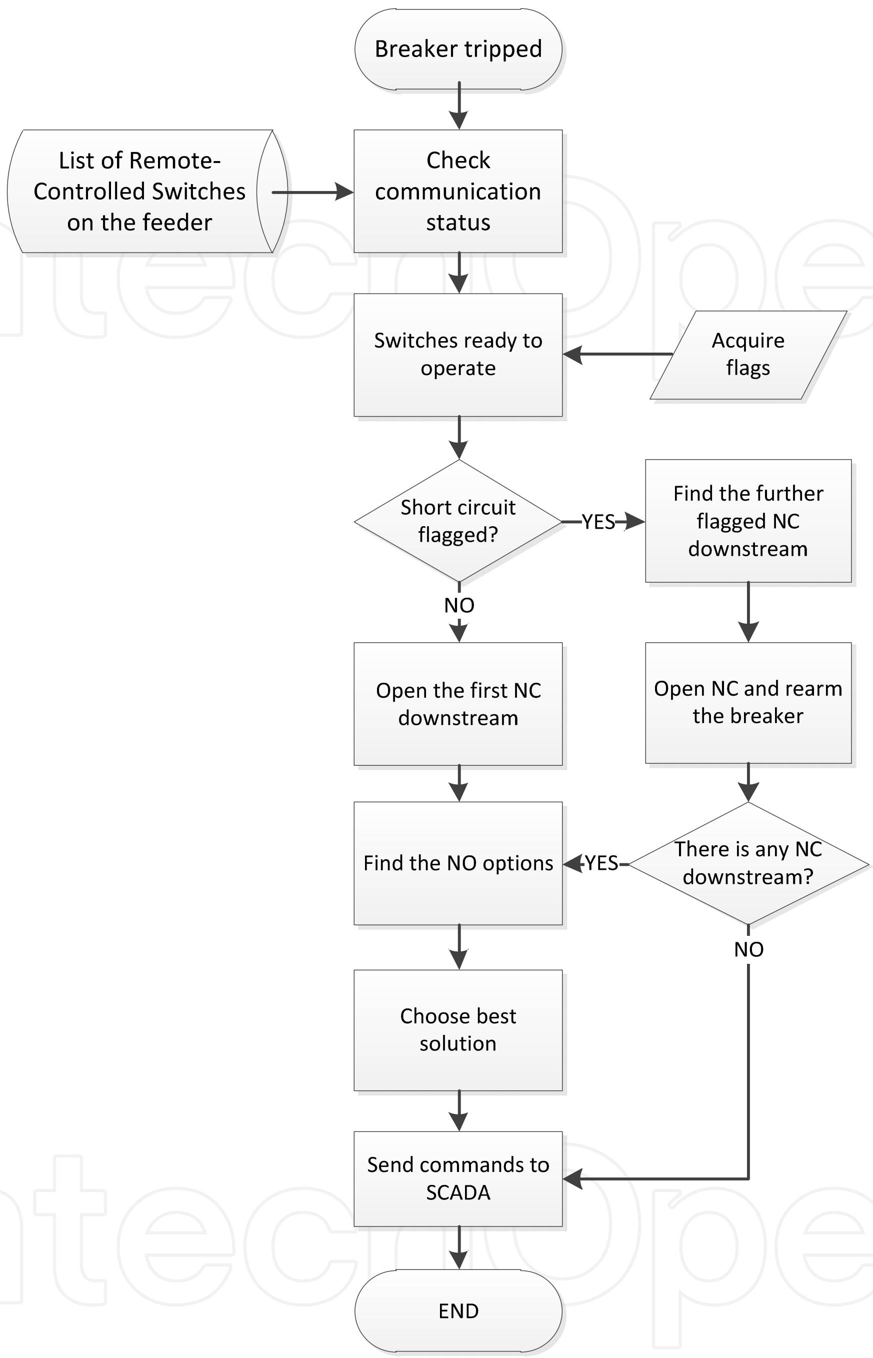

Fig. 3. Flowchart of the proposed methodology.

5. Methodology to determine the optimized reconfiguration based on the AHP method

After a contingency, the challenge is to decide which is the best load transfer scheme using the remote controlled switches among all possibilities, depending on previously defined objective functions and constraints. This is a multiple criteria decision making problem, since various types of objective functions can be considered.

The most common objectives are the maximization of restored consumers and of restored energy; however, generally it is not possible to optimize the grid for both objectives simultaneously. Furthermore, it is also important to ensure the reliability of distribution systems, through continuity indicators. The basic parameters are the SAIDI (System Average Interruption Duration Index) and the SAIFI (System Average Interruption Frequency Index), according to (Brown, 2009). In this approach, we adopt expected values based on the system's failure probability.

The constraints considered are the maximum loading of electrical elements, the protection settings and the allowable voltage drop in the primary network. Typically, the last two restrictions are the hard ones. On the other hand, a percentage of overloading of the network elements is acceptable in a temporary situation, assuming that the fault can be fixed in a couple of hours.

In our approach the following objective functions and constraints were defined to be used in the analysis of load transfers in case of contingencies:

Objective functions:

- Maximization of the number of restored consumers;
- Maximization of the amount of restored energy;
- Minimization of the expected SAIFI:

$$ESAIFI = \frac{\text{Expected Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}} \tag{7}$$

Constraints:

- Current magnitude of each element must lie within its permissible limits:

$$|I_i| \leq I_{i\,max} \tag{8}$$

- Current magnitude of each protection equipment must lie within its permissible limits:

$$|I_i| \leq I_{jprot} \tag{9}$$

- Voltage magnitude of each node must lie within its permissible ranges:

$$V_{j\,min} \leq V_j \leq V_{j\,max} \tag{10}$$

where:

ESAIFI - expected value of system average interruption frequency (failures/year);

I_i - current at branch i;

$I_{i\,max}$ - maximum current accepted through branch i;

I_{jprot} - pickup current threshold of the protection device j;

V_j - voltage magnitude at node j;

$V_{j\,min}$ - minimum voltage magnitude accepted at node j;

$V_{j\,max}$ - maximum voltage magnitude accepted at node j.

The verification of the objective functions and constraints is made by calculation of the load flow for the various alternatives in real time. The ESAIFI is obtained by applying the classical equations of reliability during the process of calculating the load flow (Tsai, 1993).

Identifying the best option for load transfers is not simple since three objective functions are employed. For example, one particular option may have the largest number of consumers to be transferred, the other the largest amount of energy to be transferred, and the other the least expected value of consumers interrupted per year.

To solve this, the Analytic Hierarchical Process - AHP method was chosen, because of its efficiency in handling quantitative and qualitative criteria for the problem resolution. The first step of the AHP is to clearly state the goal and recognize the alternatives that could lead to it. Since there are often many criteria considered important in making a decision, the next step in AHP is to develop a hierarchy of the criteria with the more general criteria at the top of it. Each top level criteria is then examined to check if it can be decomposed into subcriteria.

The next step is to determine the relative importance of each criterion against all the other criteria it is associated with, i.e., establish weights for each criterion. The final step is to compare each alternative against all others on each criterion on the bottom of the hierarchy. The result will be a ranking of the alternatives complying with the staged goal according to the defined hierarchy of the criteria and their weights (Baricevic et al., 2009).

In the proposed approach, the main criterion is to choose the best option for load transfers and the subcriteria are the proposed objective functions. The alternatives are the options for load transfers.

An example of the AHP algorithm is defined in (Saaty, 1980):

1. The setup of the hierarchy model.
2. Construction of a judgment matrix. The value of elements in the judgment matrix reflects the user's knowledge about the relative importance between every pair of factors. As shown in Table 1, the AHP creates an intensity scale of importance to transform these linguistic terms into numerical intensity values.

Intensity of Importance	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between adjacent scale values

Table 1. Intensity scale of importance (Yang & Chen, 1989).

Assuming $C_1, C_2, \ldots, C_n$ to be the set of objective functions, the quantified judgments on pairs of objectives are then represented by an n-by-n matrix:

$$\mathbf{M} = \begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_n \end{array}\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \quad (11)$$
$$\quad C_1 \quad C_2 \quad \cdots \quad C_n$$

Where n is the number of objective functions and the entries $a_{i,j}$ ($i, j = 1, 2, \ldots, n$) are defined by the following rules:

- if $a_{i,j} = \alpha$, then $a_{j,i} = 1/\alpha$, where α is an intensity value determined by the operators, as shown in Table 1;
- if C_i is judged to be of equal relative importance as C_j, then $a_{i,j} = 1$, and $a_{j,i} = 1$; in particular, $a_{i,i} = 1$ for all i.

3. Calculate the maximal eigenvalue and the corresponding eigenvector of the judgment matrix **M**. The weighting vector containing weight values for all objectives is then determined by normalizing this eigenvector. The form of the weighting vector is as follows:

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad (12)$$

4. Perform a hierarchy ranking and consistency checking of the results. To check the effectiveness of the corresponding judgment matrix an index of consistency ratio (*CR*) is calculated as follow (Saaty & Tran, 2007):

$$CR = \frac{\left(\frac{\lambda_{max} - n}{n-1}\right)}{RI} \quad (13)$$

where:
λ_{max} = the largest eigenvalue of matrix **M**;
RI = random index.

A table with the order of the matrix and the *RI* value can be found in Saaty, 1980. In general, a consistency ratio of 0.10 or less is considered acceptable.

The AHP method was implemented in the proposed methodology. Its application is presented considering the example of distribution network illustrated in Figure 4. Normally close (NC) switch and normally open (NO) switches are remotely controlled.

The main goal is to define the best option for load transfer, considering that an outage has occurred in the feeder F1 (fault upstream of NC-1). In this case, there are two transfer options:

a. open the NC-1 switch and close the NO-1 switch; or
b. open the NC-1 switch and close the NO-2 switch.

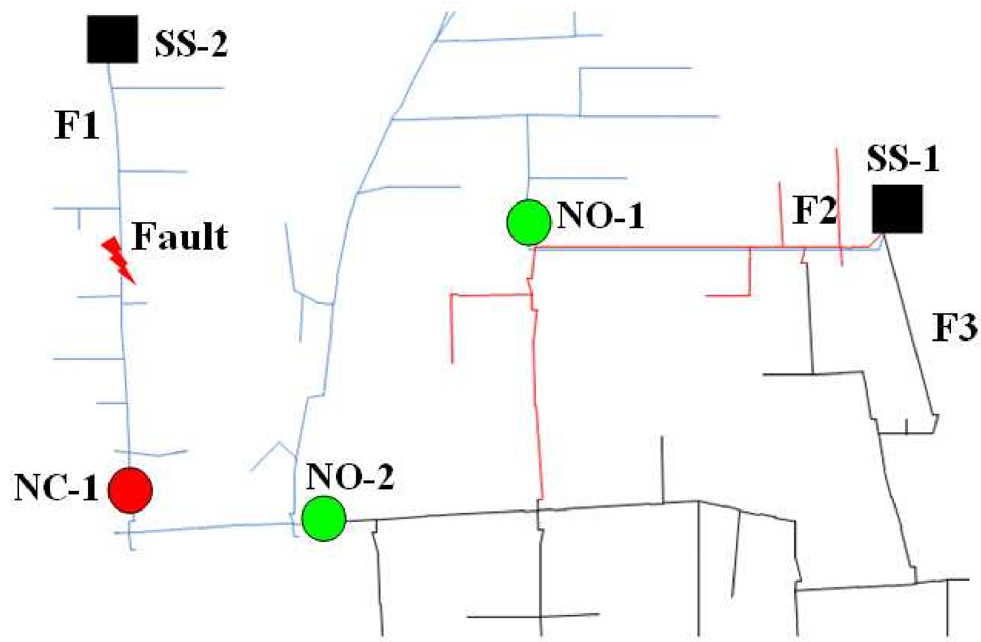

Fig. 4. Distribution network with three feeders.

First, the judgment matrix was obtained:

$$\mathbf{M} = \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & C_2 & C_3 \end{array} \\ \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix} \end{array} \tag{14}$$

where:
M = judgment matrix;
C_1 = number of restored consumers;
C_2 = amount of restored energy;
C_3 = expected number of interrupted consumers per year.

Thus, the weight values for the three objective functions were determined:

$$W = \begin{bmatrix} 0.64 \\ 0.26 \\ 0.10 \end{bmatrix} \tag{15}$$

where:
$\lambda_{\max} = 3.07$.

The consistency ratio (*CR*) was calculated by Equation 13:

$$CR = \frac{\left(\frac{3.07 - 3}{3 - 1} \right)}{0.52} = 0.0673 \tag{16}$$

The consistency ratio is lower than 0.10 and it is considered acceptable.

Tables 2 and 3 show the results of the analysis for each load transfer. In this example, there is no violation on the constraints.

Options	Number of Restored Consumers	Amount of Restored Energy (kW)	Expected Number of Interrupted Consumers per Year
1 (open NC-1 and close NO-1)	14,000	1,930.00	1,800
2 (open NC-1 and close NO-2)	14,000	1,930.00	2,300
Base Selected	14,000	1,930.00	1,800

Table 2. Results of the analysis for each load transfer.

Options	Number of Restored Consumers	Amount of Restored Energy	Expected Number of Interrupted Consumers per Year
1	1.00	1.00	1.00
2	1.00	1.00	0.78

Table 3. Normalized values of Table 2.

The results using AHP method were obtained by Equation 17:

$$\begin{bmatrix} Op.1 \\ Op.2 \end{bmatrix} = \begin{bmatrix} 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 0.78 \end{bmatrix} \cdot \begin{bmatrix} 0.64 \\ 0.26 \\ 0.10 \end{bmatrix} = \begin{bmatrix} 1.00 \\ 0.98 \end{bmatrix} \quad (17)$$

According to the proposed method the option "1" is considered the best solution. Thus, the system performs the commands to make the load transfer, open NC-1 and close NO-1, without violating the set of constraints.

6. Experimental analysis

To verify the performance of the proposed methodology several case studies were carried out in the concession area of a power utility in Brazil. The developed methodology was applied on the distribution system shown in Figure 5, which has 20 distribution substations, 125 feeders, 214 remote controlled switches, and 523,619 consumers.

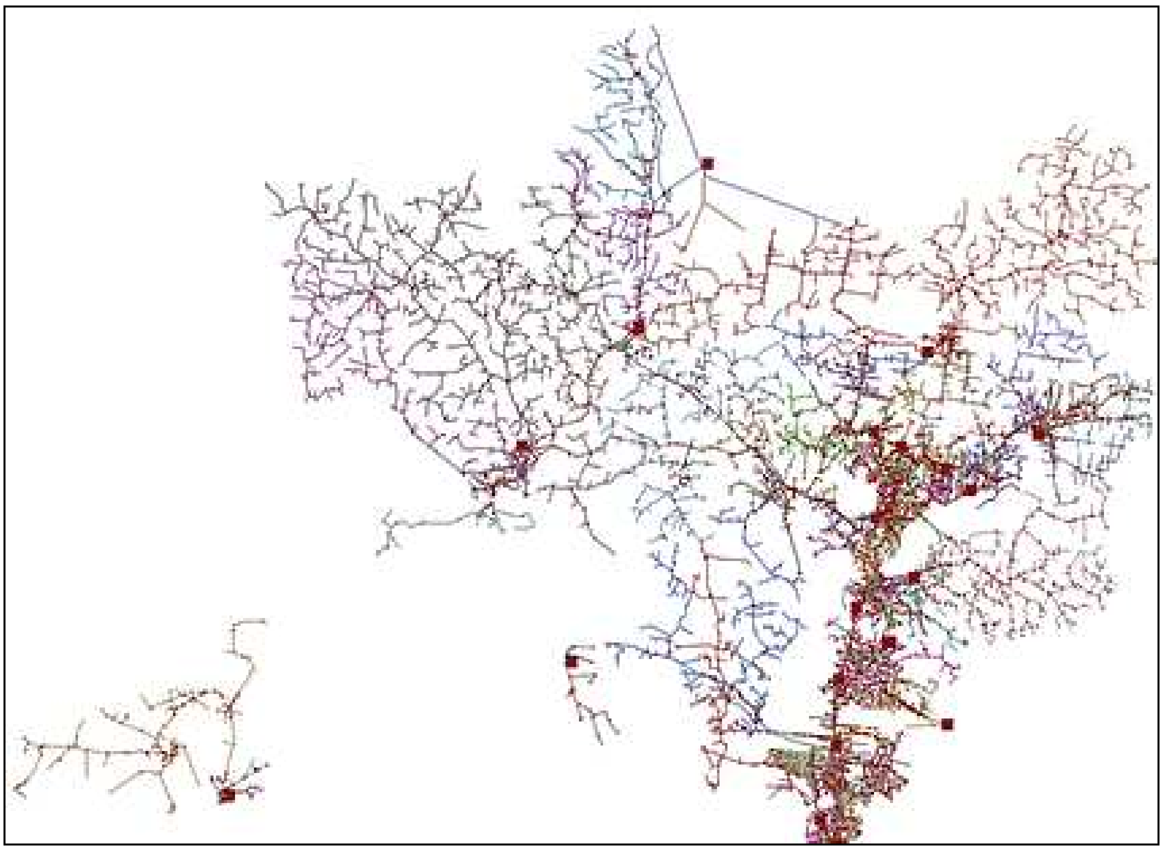

Fig. 5. Distribution network of a power utility in Brazil.

Figures 6 and 7 show the results for the calculation of load flow and the typical load curves used, respectively:

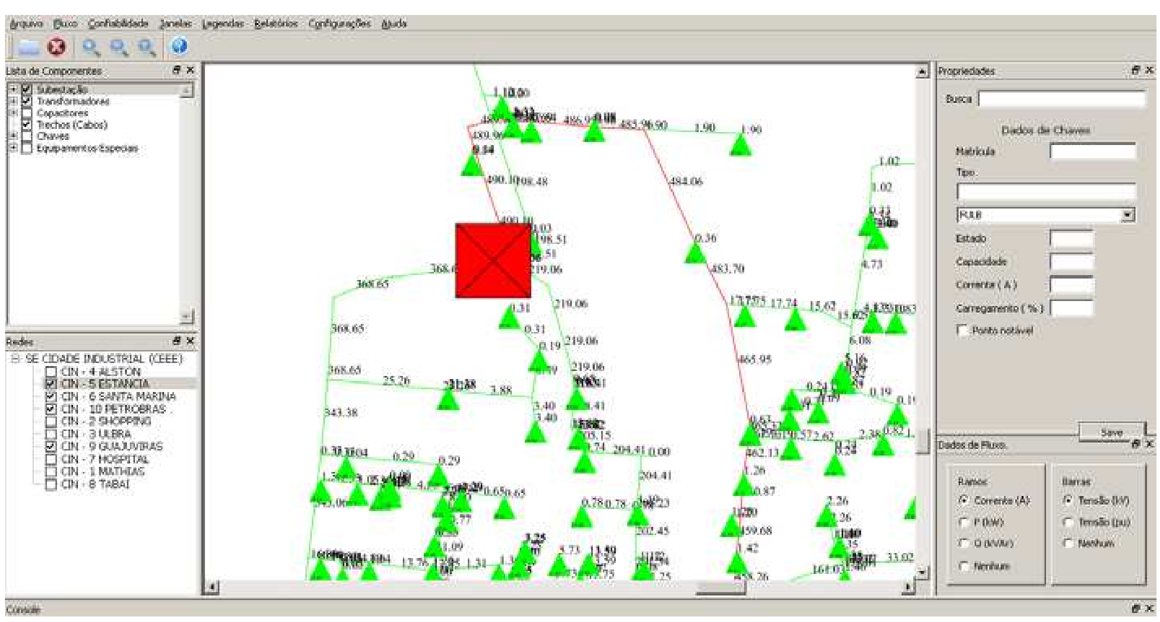

Fig. 6. Results for the calculation of load flow with the indication of values of current in branches and voltage in nodes.

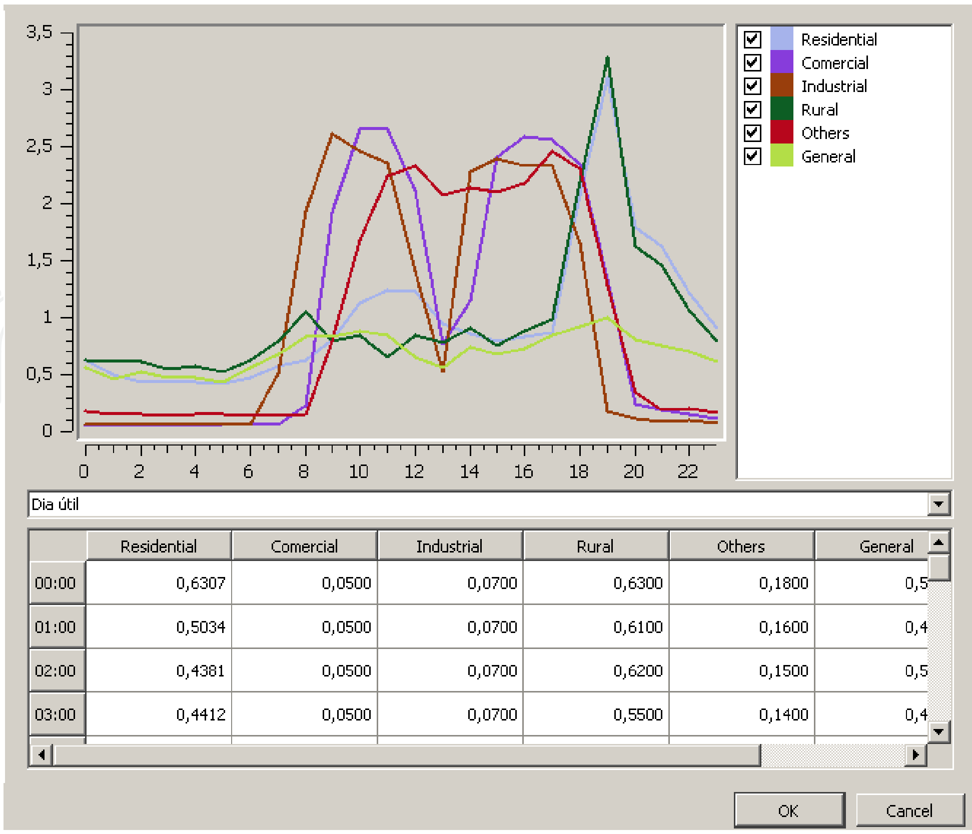

Fig. 7. Typical load curves used.

Table 4 shows the results obtained by the application of this methodology in case of outage of a feeder when considering the power restoration time.

Description	Mean Time to Restore Energy			
	Faults upstream the NC switch		Faults downstream the NC switch	
	Clients upstream the switch	Clients downstream the switch	Clients upstream the switch	Clients downstream the switch
Before installing the remote controlled switches	1h54min	58min	43min	1h34min
After installing the remote controlled switches	1h54min	0min	0min	1h34min
Reduction	-	58min	43min	-

Table 4. Results obtained with the use of remote controlled switches.

It should be noted that a reduction of approximately 30 % on the annual SAIDI index of this system is expected, assuming the number of faults in the main feeder.

Figures 8 and 9 show the picture of a pole top remote controlled switch been installed and the screen of the SCADA system, respectively:

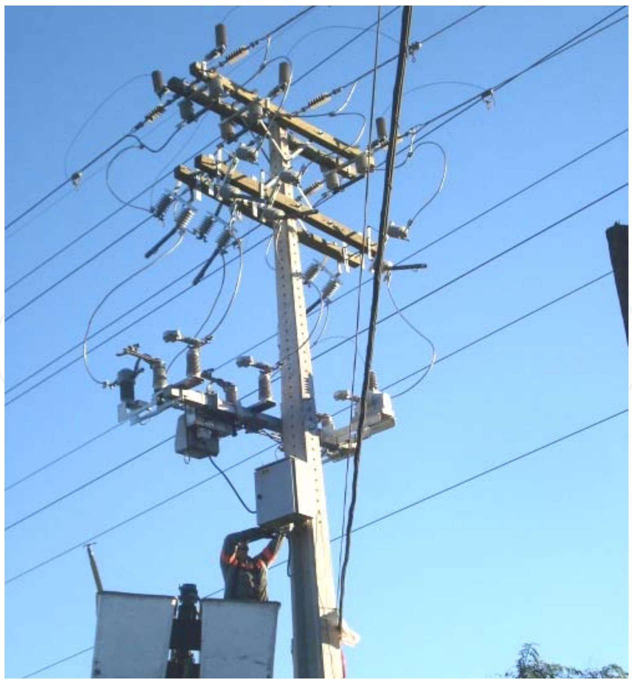

Fig. 8. Installation of a remote controlled switch.

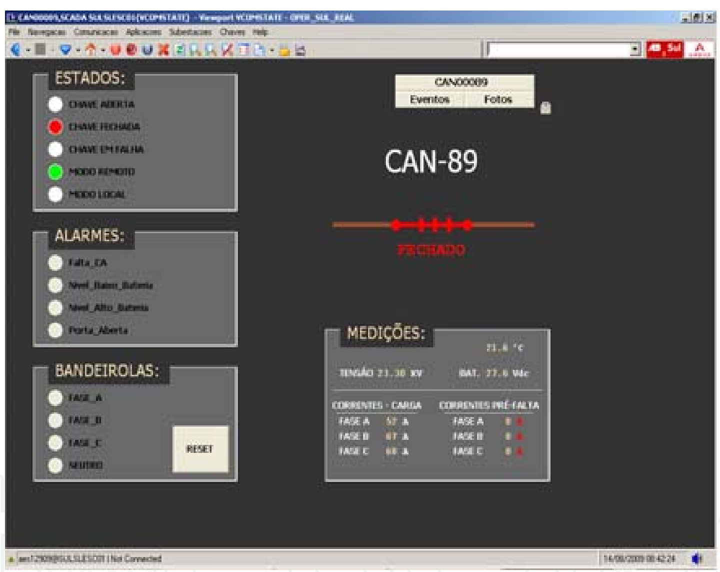

Fig. 9. Screen of the SCADA system.

7. Conclusion

This work presented a methodology developed for automatic power restoration system, which operates remote controlled switches in the distribution network. It was show how to assess the technical feasibility of the load transfers in real time by means of computer simulations, and how the best maneuver option to execute after a contingency is defined based on the AHP multicriterial method. The system will automatically handle the load transfers in accordance with the defined objective functions, without violating the established constraints. Case studies with real data from utilities were conducted to evaluate the performance of software developed presenting satisfactory results.

8. Acknowledgment

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