INTELLIGENT SYSTEM FOR AUTOMATIC RECONFIGURATION OF DISTRIBUTION NETWORK IN REAL-TIME

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ABSTRACT

In normal operation, the reconfiguration of distribution network can reduce losses, balance loads and improve quality indicators. The increasing use of remote controlled equipment in power systems leads the development of more efficient techniques for automatic reconfiguration of network, being particularly important in Smart Grid applications. This paper presents a methodology and system for automatic reconfiguration of distribution network in real-time. The optimization of the network performance is based on a heuristic method and multicriterial analysis. The developed algorithms are integrated into a supervisory system, which allows real-time measurements and commands to the equipment. The proposed methodology is tested in a real network of a power utility and results are presented and discussed.

1. INTRODUCTION

The need to improve the quality and reliability of power systems has contributed to the advancement of researches on Smart Grid and has been favored by the increased use of resources related to information technology and automation [1]. Smart Grid has a direct impact on information systems and automation of power utilities, for instance in the supervisory, data acquisition and remote controlled equipment (and others which use some advanced metering infrastructure), or in operation and services (management, planning, engineering, maintenance, billing, etc.).

Smart Grid is characterized by a series of integrated technologies, methodologies and procedures for planning and operation of electrical networks. One of its main features is that it should be reconfigurable, quickly and flexibly, in the event of changes in service conditions [2].

Reconfiguration of distribution network performs an important role in this context, which can change the topology by opening or closing switches, allowing to isolate faults and to restore the supply in contingency situations, and also in cases of scheduled shutdowns. In addition, in normal operation, the change of topology allows a better load balancing between feeders, transferring consumers of heavily loaded feeders to lightly loaded feeders, thus improving voltage levels and reducing losses. Several researches are related to the reconfiguration of distribution network, based on mathematical methods, heuristics and artificial intelligence techniques [3].

In recent years, new methodologies of reconfiguration of distribution network have been presented, exploring the greater capacity and speed of computer systems, the increased availability of information and the advancement of automation, particularly, the SCADA (Supervisory Control and Data Acquisition). With the increased use of SCADA and distribution automation through remote controlled equipment, the reconfiguration of distribution network becomes more viable as a tool for planning and control in real-time. Most of recent researches [4-6], however, do not take into account reconfiguration in real-time. The works of Wang et al. [7] and Lopez et al. [8] present an online reconfiguration approach, the first with emphasis on the reduction of load flow calculation time and the later on the demand characterization. Recently, Vargas and Samper [9] presented fast algorithms for a smart distribution management system, which include load estimation, load flow calculation and optimal feeder reconfiguration. In these works, however, the optimization approach is for monocriterial analysis, and some feasibility aspects for real-time application are not taken into account, such as a proper definition of the frequency of reconfiguration and the coordination of protection devices.

In this work, a methodology and a computational tool for automatic reconfiguration of distribution network in real-time is developed, from the standpoint of Smart Grid. The research uses the information and functionality of remote controlled equipment installed in distribution systems, applying them in a computer system that allows the reconfiguration of the network in normal operation.

The main contributions of this paper are highlighted as follows:

- a new methodology for the automatic reconfiguration of distribution network in real-time;
- a multicriterial decision making method, AHP - Analytic Hierarchic Process, applied to the reconfiguration of distribution network;
- a computer analysis integrated with supervisory control and data acquisition (SCADA) of remote controlled switches to allow performing automatic

reconfiguration in real-time.
The proposed methodology is tested in a real distribution network, ensuring the practical applicability of the heuristic optimization algorithm employed.

2. METHODOLOGY FOR DISTRIBUTION NETWORK RECONFIGURATION

The reconfiguration of distribution network can be characterized as an optimization problem. To improve network performance, one or more objectives (e.g. reduce losses and improve reliability) are established, and then one verifies which configuration produces the best result, without violating constraints on proper and safe operation of the network. This configuration is defined, then, as the optimal solution for the system. When more than one objective is set, the analysis should incorporate methods for multicriteria decision making, which may include expert opinion on the definition of a preference for one objective over another.
In this work, the developed optimization algorithm is based on a heuristic method and on the AHP multicriterial decision making method to identify the best network configuration. The diagram in Fig. 1 shows the architecture employed in this work.

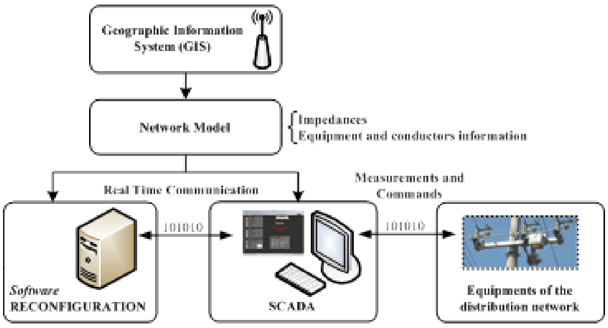


Fig. 1. Architecture of the proposed system.

The initial assumption is that only remote controlled devices - such as switches and reclosers - are considered in the optimization process. This allows automatic reconfiguration without requiring displacement of crew for operating equipment. Moreover, it is also important to use the information available in remote measuring equipment, which allows the determination of the current state of the network, especially in terms of demanded power and topology. The SCADA program is the main interface between the reconfiguration program developed and the equipment in network.

2.1 Objective Functions and Constraints

In this work, the following objective functions are defined for the reconfiguration of distribution network in normal operation:
- Minimization of Energy Losses (kWh):

$$\min \quad E_{losses} = 3 \cdot \sum_{k} r_k \cdot {I_k}^2 \cdot \Delta t \qquad (1)$$

- Minimization of the Expected System Average Interruption Frequency Index (failures / year):

$$\min \ E_{SAIFI} = \frac{\sum_{n} \sum_{j} \left(\lambda_{jn} \cdot \ell_{\text{Protjn}} \cdot C_{\text{Protjn}}\right)}{C_S} \qquad (2)$$

- Minimization of the Expected Energy Not Supplied (MWh / year):

$$\min \ E_{ENS} = \sum_{n} \sum_{j} \lambda_{jn} \cdot \ell_{\text{Protjn}} \cdot L_{jn} \cdot d_{jn} \qquad (3)$$

Where:
I_k: current at branch “k”;
r_k: resistance of branch “k”;
Δt: duration of the load rate considered;
λ_{jn}: failure rate of protection device “j” at feeder “n”;
l_{Protjn}: length of the branches protected by the protection device “j” at feeder “n”;
C_{Protjn}: number of customers downstream of the protection device “j” at feeder “n”;
C_s: total number of customers served;
L_{jn}: interrupted power by the protection device “j” at feeder “n”;
d_{jn}: average interruption duration of protection device “j” at feeder “n”.

Additionally, the following constraints must be observed:
- radial network;
- current magnitude of each element must lie within its permissible limits;
- current magnitude of each protection equipment must lie within its permissible limits;
- voltage magnitude of each node must lie within its permissible ranges.

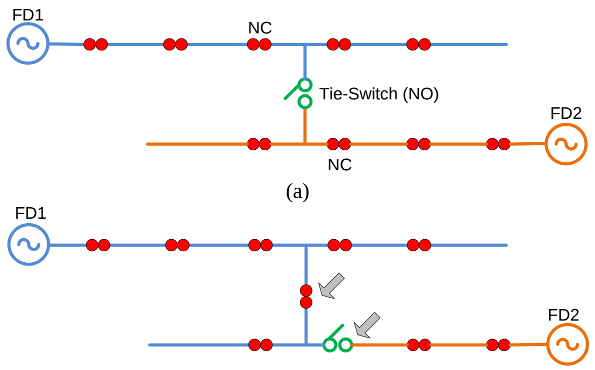
For obtaining load flow values in the distribution system, the proposed algorithm implements the classical backward/forward sweep method [10], which is suitable for calculation of reverse flows from distributed generation. With load flow values, the energy losses for the distribution system are obtained. Violation of limits related to constraints is prohibited.

2.2 Heuristic Technique for Selecting Configurations

The optimization technique employed in this work is based on the Branch Exchange adaptation proposed by [11] which has the following advantages over other techniques from the literature:
- it highly limits the search space of solutions, reducing calculation and computational processing time;
- it does not require adjustments of optimization parameters due to changes in the network (such as grid expansion or installation of new equipment,)
- the radial network is guaranteed, without the need to verify if the combination of switches that comprise the topology tested is valid.

The optimization algorithm can be described in four steps:
- Step 1: from the initial network topology (Fig. 2a), close a normally open (NO) tie-switch and open the first normally closed (NC) switch downstream (Fig. 2b). Go to Step 2.
- Step 2: calculate the indicators of objective functions (Elosses, ESAIFI and EENS). If there is no improvement in indicators, repeat Step 1, but reversing the direction of analysis (Fig. 2c). If after repeating the process there is no improvement in either direction, the algorithm is terminated and the final solution is the current configuration. If there is improvement in indicators and there is no violation of the constraints, go to Step 3.
- Step 3: Close the switch opened in the previous step, and open the first NC switch downstream, keeping the direction of one feeder to the other (Fig. 2d). Perform the calculations and evaluate the improvement in the objective functions indicators. If there is no improvement, the algorithm terminates and the topology found in Step 2 is defined as the final topology. If there is improvement without constraints violation, go to Step 4.
- Step 4: Repeat the procedure while there is improvement in indicators, without violation of the constraints: close the switch opened in the previous step, open the first NC downstream and calculate the indicators. If there is no improvement in indicators, or there is any violation of the constraints, the final solution is the topology found in the previous cycle.

The methodology assumes that only the remote controlled switches are analyzed and it consists in applying the branch exchange algorithm twice: first, to determine the individual result of each configuration test, and after to determine the final combination of configurations. In the first case, the procedure is repeated for each normally open tie-switch, starting from the initial network topology. At the end of this process it is applied the multicriteria decision method described in the next section, to define the best sequence of switching. The procedure of optimization is then applied for the second time, but for each tie-switch tested, the analysis is made without returning to the initial configuration.



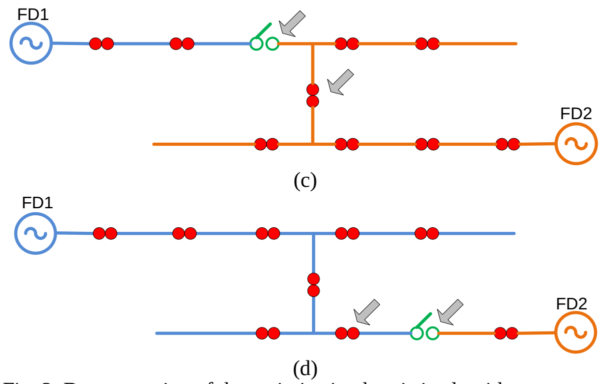


Fig. 2. Demonstration of the optimization heuristic algorithm.

2.3 AHP Method for Multicriterial Decision Making

The objective of this step of the optimization process is to determine the final sequence of switching, depending on the individual results obtained from the branch exchange method. The proposal is to assort the sequence of switching in order of the best results.
In this work, the algorithm chosen was the AHP (Analytic Hierarchic Process) method [12]:
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 Tab. 1, the AHP creates an intensity scale of importance to transform these linguistic terms into numerical intensity values.

TABLE 1
Intensity Scale of Importance

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

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

$$M = \begin{array}{c} \\ c1 \\ c2 \\ \vdots \\ cn \end{array} \begin{array}{c} \begin{array}{cccc} c1 & c2 & \cdots & cn \end{array} \\ \begin{pmatrix} 1 & a12 & \cdots & a1n \\ 1/a12 & 1 & \cdots & a2n \\ \cdots & \cdots & 1 & \cdots \\ 1/a1n & 1/a2n & \cdots & 1 \end{pmatrix} \end{array} \tag{4}$$

Where n is the number of objective functions and the entries $a_{i,j}$ (i, j = 1, 2, …, 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 Tab. 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:

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{5}$$

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

$$CR = \frac{\left(\dfrac{\lambda_{\max} - n}{n-1}\right)}{RI} \tag{6}$$

Where:

$\lambda_{\max}$: the largest eigenvalue of matrix M;

RI: random index.

In general, a consistency ratio of 0.10 or less is considered acceptable.

In this work, the multicriteria analyzed are:

$$\begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix} = \begin{bmatrix} 0.64 \\ 0.26 \\ 0.10 \end{bmatrix} \tag{7}$$

Where:
W1: Energy losses
W2: Expected System Average Interruption Frequency Index
W3: Expected Energy Not Supplied

3. CASE STUDY AND RESULTS

The proposed methodology was verified through several tests on the concession area of a power utility of Brazil. The real distribution network model presented in Fig. 3 is used as a case study. This network has 2 substations, 5 feeders, 3 distributed generators of 1 MW each, 15 tie-switches, 99 normally closed switches and over 21,000 consumers. The switches are remote controlled.

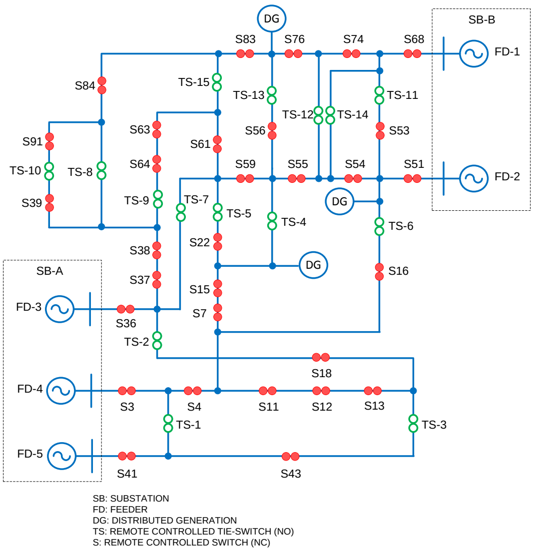


Fig. 3. Distribution network.

The individual analysis of the tie-switches leads to the results presented in Tab. 2. Only the cases where the three criteria analyzed presented positive evolution are shown.

TABLE 2
Results for the Individual Analysis of Tie-switches

Options	Switching with best result	Energy Losses (kWh)	ESAIFI (failures/yr)	EENS (MWh)
Initial Config.	-	1,260.72	11.95	485.9
Option 1	Close TS-1 / Open S3	1,365.43	11.71	404.6
Option 2	Close TS-2 / Open S13	1,339.27	11.70	393.5
Option 3	Close TS-3 / Open S11	1,282.99	**10.99**	363.3
Option 4	Close TS-8 / Open S84	**867.48**	11.27	**350.0**
Option 5	Close TS-9 / Open S64	1,380.33	11.63	415.7
Option 6	Close TS-10 / Open S91	921.78	11.24	352.1

Each result in Tab. 2 is normalized by the minimum value found in the tests and using the weight vector presented in Eq. 7, the ordination of the switching sequence through the AHP method is found by:

$$P = \begin{bmatrix} 0.64 & 0.94 & 0.87 \\ 0.65 & 0.94 & 0.89 \\ 0.68 & 1.00 & 0.96 \\ 1.00 & 0.98 & 1.00 \\ 0.63 & 0.94 & 0.84 \\ 0.94 & 0.98 & 0.99 \end{bmatrix} \cdot \begin{bmatrix} 0.64 \\ 0.26 \\ 0.10 \end{bmatrix} = \begin{bmatrix} 0.7371 \\ 0.7477 \\ 0.7891 \\ 0.9935 \\ 0.7321 \\ 0.9559 \end{bmatrix} \tag{8}$$

where the 6 x 3 matrix represents the normalized values of Tab. 2.

The results must be ordered from the highest to the lowest value, which leads to the following sequence:

Option 4 (TS-8), Option 6 (TS-10), Option 3 (TS-3), Option 2 (TS-2), Option 1 (TS-1) and Option 5 (TS-9). The Branch Exchange algorithm is then reapplied according to this sequence; the difference in relation to the previous analysis is that now the best configuration obtained with one test is maintained as the initial configuration for the next test. The final result is presented in Tab. 3. In this stage, switching tests on TS-2 (Option 2) and TS-9 (Option 5) did not improve the objective functions and they are not shown in Tab. 3.

TABLE 3
Final Results of Reconfiguration Analysis

Sequence of test	Switching with best result	Energy Losses (kWh)	ESAIFI (failures/yr)	EENS (MWh)
Initial Config.	-	1,260.72	11.95	485.9
Option 4	Close TS-8 / Open S84	867.48	11.27	350.0
Option 6	Close TS-10 / Open S91	865.37	11.27	350.0
Option 3	Close TS-3 / Open S11	767.64	10.31	295.8
Option 1	Close TS-1 / Open S3	**760.18**	**10.23**	**291.7**
Final Reduction (%)		39.7%	14.39%	39.96%

All procedures of the main program have been successful and the final topology of the network determined by the program improved the indicators of the objective functions of the optimization method, with no constraints in relation to the necessary switching. The tests were performed in about 3 minutes in a PC with Intel Core (modelo), 3.33 GHz and 24G RAM. The scale of few minutes is acceptable for the proposed application.

4. CONCLUSIONS

This paper presented a methodology for automatic reconfiguration of distribution network. With the application of the methodology, it was shown that it is possible to improve network performance indicators, such as reducing losses and increasing reliability. The switching is performed automatically in the sequence determined by the program. For a real evaluation of the system performance, case studies were performed with real data from a power utility. The results indicate the feasibility of the methodology.

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