Memorias del XVI Congreso Latinoamericano
de Control Automático, CLCA 2014
Octubre 14-17, 2014. Cancún, Quintana Roo, México

Service Restoration in Distribution Networks Considering Distributed Generation

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Abstract: In this article an electric power service restoration model for distribution networks considering distributed generation (DG) is presented. The optimization model is based on genetic algorithms (GA), using the fundamental loops of the network as the topology selection mechanism. The algorithm was tested on IEEE test systems with17 and 33 buses. Results show the advantages of DG in the restoration process and the effectiveness of the study technique.

Keywords: Distribution Network, Service Restoration, Distributed Generation, Genetic Algorithms.

1. INTRODUCTION

The occurrence of an interruption in electric power service is one of the most complex aspects faced by distribution companies due to the wide variety of possible causes (Quiroga et al. 2011).

With the aim of reducing both financial and social costs, most electricity companies have pre-established guidelines and operational procedures for solving this problem. These procedures provide a sequence of steps to be followed by an operator to achieve an objective. However, given the highly variable conditions resulting from a fault and the fact that the restoration procedures are based on predicted system conditions, the results obtained are not always favourable.

Resolving the electric power supply restoration problem is a process that can take hours as there are several actions that must be carried out. The first step is the diagnostic of the fault using the data available in the control center and the alarms, normally gathered by SCADA systems, which must then be processed and interpreted. Current information and communications technology provides the operators at the control center with powerful automatic devices and support systems for these purposes (Sudhakar et. Al 2011).

The main objective in restoring service is to re-establish the electric power service at the highest level of system load possible, through network reconfiguration without breaking operating conditions (Adibi 2000).

A large amount of research has been published on the service restoration problem, a significant part of which has been compiled into sets of bibliographic reviews that present the mathematical formulation, the problem resolution methods and in general, the background to the research and development in the field of the service restoration problem. The study presented by Ćurčić et al. 1995 is a bibliographic review that covers 1988 to 1994, while the article published by M. M. Adibi 2000 covers 1981 to 1997, and finally, the work developed by Sudhakar et al. 2011 is a bibliographic review for the years 1988 to 2007.

In general, the restoration problem has been approached as an optimization problem that minimizes or maximizes an objective function subject to certain restrictions. Traditionally the parameters of restored power or system reliability are maximized; or minimization is performed on a loss function, the number of operations or restoration time. The technical restrictions applied are: voltage limits, current limits for lines, the radial topology of the network, client prioritization, restoration costs, line capacity, etc.

Regarding the techniques used for optimization processes, there are several alternatives, for instance: knowledge-based, expert systems, heuristic techniques, Fuzzy logic, Petri net, Genetic Algorithms, Ant colony, Tabu search, Artificial neuronal networks and Hybrid models (Sudhakar et al. 2011).

Since 2005, the concept of Multi-Agent Systems (MAS) has been introduced into the set of methods used to solve the restoration problem. Multi-agent systems stem from the formalization of artificial intelligence and distributed computation-based applications, mainly with the aim of decentralizing the restoration decision-making process (Li et al. 2010)-(Lo et al. 2010).

In recent years, the search for new alternatives to improve the performance of restoration algorithms has continued. The most recent are multi-objective models based on the Non-Sorting Genetic Algorithm II (Kumar et al. 2008), the Fuzzy Grey approach (Chen 2010) and Genetic Algorithms (Michibita et al. 2011).

Over time, and with the implementation of public policies that give incentives to the use of Renewable Energy, we have seen an increasing prevalence for Distributed Generation (DG), i.e. small electric power generation units located close to clients; these are changing network operations (Ackermann 2001) and (Mendoza et al. 2014).

The present study develops a new electric power service restoration model for a medium voltage distribution network, taking into account the existence of DG. The proposal uses GA as an optimization technique along with a loop vector system (Mendoza et al. 2006 and 2009). This allows for an efficient search for structures that provide service restoration. The technique is more efficient for the case of multiple system faults, which represents an advantage over other techniques.

2. PROBLEM FORMULATION

Many objective functions has been considered in the service restoration problem, the most used are maximize the restoration zone and reduce the restoration time (switching operation).

But in this work, considering that the automatization level of the distribution network increase each days, the objective function considered is to maximize the restoration zone and minimize the distribution power losses of the network. In the maximizing the restoration zone, a process of minimization of the affected zone is developed using routing algorithms to select the sectionalizers closest to the failure. Then, a metaheuristic technique is used to find the best topology to minimize the active power losses of the system, see eq. (1).

Moreover, a set of the constraints is used to maintain correct operation of the network. Equation (2) represents the node matrix of the current balance of the system. One the other hand, considering that the current of each lines is related with the topology of the network, the equation (3) is used for represents the thermal limit of the feeder and the maximum capacity of the substation. At the same ways, with the changing topology of the networks is possible affect the node voltages, for this reason the equation (4) is used to considers the voltage restriction of each node. Finally the equation (5) describes the radial nature of the primary distribution system that is necessary to maintain the protection scheme operation correctly.

$$Minimize \quad \sum_{b=1}^{Nr} R_b \cdot i_b^2 \tag{1}$$

$$A \cdot i = I \tag{2}$$

$$i \leq i_{\max} \tag{3}$$

$$v^{\min} \leq v \leq v^{\max} \tag{4}$$

$$M = N - N_f \tag{5}$$

Where:

R_b :"b" branch resistance

i_b : "b" branch complex current

i, i_{max} :Current vector and maximum current of branches

I : Vector of node currents

A : Incidence matrix

v : Node voltage

v^{min} : Node minimum voltage

v^{max} :Node maximum voltage

M : Radial net branch number

N : Node number

N_f : Source number

N_r : Total branch number

3. PROPOSED SOLUTION

This study is based on the distribution network reconfiguration presented in (Mendoza et al. 2006), which uses genetic algorithms for optimization along with meshed network information vectors that efficiently guide the search for radial topology. Genetic algorithm is a technique based on the Theory of Evolution. It can be applied to a wide range of engineering problems with excellent results.

3.1 Encoding and genetic operators

This proposal takes into account the network's fundamental loop vectors (FL) in order to generate radial topologies. The FL are defined as a set of arcs that form a closed path on the circuit, with the condition that they do not contain any other closed path within them. The FL of a circuit can be used to create radial topologies, selecting an element from each FL. A topology is represented in the form of a string of real numbers, each of them representing the elements that must be open in order to produce a radial system. This methodology was used in Mendoza et al. 2006 and 2009 with excellent results in system reconfiguration applications.

For example, if we consider the system shown in Fig. 1, the number of FL can be calculated as the number of branches minus the number of buses plus one. In this case the result is 3 and the meshes are represented by equation (6).

Based on these vectors, the lines that cannot be open must be discarded, among which are L_{12} and L13, and thus (6) can be reduced to (7). It now remains only to select an element of each FL to form a radial network.

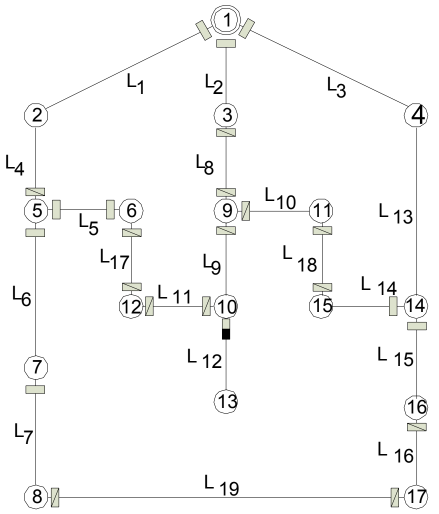

Fig. 1 IEEE 17 Civanlar Power Distribution System

$$\begin{aligned} FL_1 &= [L_1 L_2 L_4 L_5 L_8 L_9 L_{11} L_{17}] \\ FL_2 &= [L_2 L_3 L_8 L_{10}\ L_{13} L_{14}\ L_{18}] \\ FL_3 &= [L_1 L_3 L_4 L_6 L_7 L_{13} L_{15} L_{16} L_{19}] \end{aligned} \tag{6}$$

$$FL_1 = [L_1 L_2 L_4 L_5 L_8 L_9 L_{11} L_{17}]$$
$$FL_2 = [L_2 L_3 L_8 L_{10} L_{14}\ L_{18}] \quad (7)$$
$$FL_3 = [L_1 L_3 L_4 L_6 L_7 L_{15} L_{16} L_{19}]$$

$$FL_1 = [L_1 L_4 L_5 L_{17} L_{11} L_9 L_{10} L_{18} L_{14} L_3]$$
$$FL_2 = [L_1 L_3 L_4 L_6 L_7\ L_{15} L_{16} L_{19}\ ] \quad (8)$$

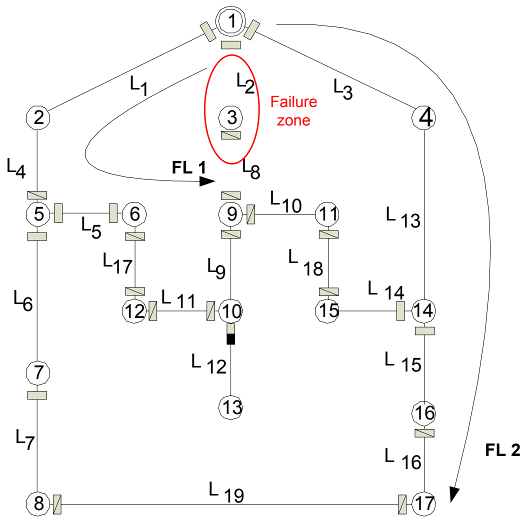

Fig. 2 Civanlar system with fault on line 2.

This procedure, developed for reconfiguration processes, has even greater potential if used for restoration processes, since the FL vectors will be reduced by the system faults and the areas that are isolated by the use of protection elements and sectionalizers. For example, if the system in Fig. 1 experiences a fault on line L_2, FL1 and FL2 will disappear from Eq. 7 creating new FLs, and will become Eq. 8, see Fig. 2. This implies that there would be a reduced number of combinations of the GA. It is important to note that under the conditions of multiple faults, the advantages would be even greater.

3.2 The DG

The DG is always considered synchronized to the network, the active and reactive power of the DG is injected as a PQ node and the system power losses are then estimated (Moghaddas-Tafreshi et. Al. 2009).

3.3 Evaluation of the Objective Function

In order to improve the decision-making process during optimization, the objective function and constraints will be evaluated using a single load flow based on a power summation method. This algorithm can be used to evaluate the active power losses in the system and its constraints.

3.4 Algorithm description

The input data for the restoration algorithm consists of the power system parameters and the general structure of the GA methodology, as shown in Fig. 4.

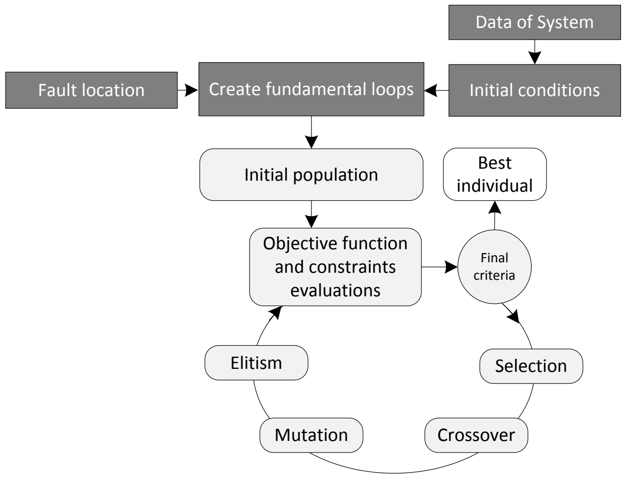

Fig. 4. Block Diagram of the proposed GA

4. APPLICATIONS

The proposed algorithms were tested on two systems. The first system is IEEE 17 named the Civanlar system, which is shown in Fig. 1.This system has an installed power of 28.47MW and 5.9 MVAr, with the initial operating condition of lines 10, 11 and 19 open, in accordance with (Mendoza et al. 2006), where the power loss is 0.4661 MW. The second test uses the Baran system shown in Fig. 5.The installed power of this system is 3.715 MW and 2.3 MVAr, with the initial condition of lines 7, 9, 14, 32 and 37 open and losses of 0.1397 MW (Mendoza et al. 2006).
The algorithm was run on a 2.0 GHz Intel® Pentium® P6100 with 2GB RAM, using the following GA parameters: number of individuals per population: 50, maximum number of generations: 100, crossover probability: 95%, mutation probability: 30%.

4.1. Civanlar System

The results obtained for restoring the Civanlar system under different faults, without considering DG and considering the initial conditions mentioned above, are presented in Table 1. It can be seen that in the case of a fault the elements that can isolate the fault have been operated.

Table 1: restoration for the civanlar system without DG

Fault on line	Close Lines	Open Lines	Losses MW	Simulation Time sec.
2	10 - 11	9	0.8494	3.13
6	19	--	0.4560	3.02
9	10	18	0.1777	3.04
18	10 - 19	7	0.5001	3.02

As can be seen in Table 1, for example, a fault on line 2 can be isolated by opening the existing sectionalizer elements at the beginning of lines 2 and 8, leaving node 3 without power. Running the restoration algorithm, the result shows it is necessary to close the sectionalizer elements on lines 10 and 11, opening the sectionalizer element on line 9. This implies that the losses on this configuration would be 0.8494 MW, with a simulation time of 3.13 seconds. This suggests that under this new topology, the losses would increase 82%.

In order to evaluate the restoration process with the incorporation of DG on the Civanlar network, DG was tested on buses 8, 12 and 17, the ends of the network, and buses 5 and 14, intermediate points on the network, with power values between 0.5 and 20 MW considered without the ability to operate in isolated mode and at unity power factor (PF), representing penetration levels of 1.7% and 70%, respectively. A fault on line 2 was considered, along with the initial condition of lines 10, 11 and 19 open. The results are shown in Table 2, showing the relationship between the best alternative to restore the system and the location of the DG, as well as the position and size with the losses obtained after restoration. This implies that the system restoration will not only depend on the location of the DG but also the power injected into the system.

Table 2: Tests on Civanlar with DG with PF = 1, Fault on Line 2

DG on Bus	MW	Close Lines	Open Lines	Losses MW	Simulation time sec.
s/GD	**-**	**10 – 11**	**9**	**0.8494**	**3.32**
5	0.5	10 – 11	9	0.7175	3.57
5	10	10 – 11	9	0.6260	3.16
5	**20**	**10 - 11 - 19**	**9 – 16**	**0.5380**	**3.19**
8	0.5	10 – 11-19	6-9	0.7068	3.47
8	**10**	**10 – 11 - 19**	**9 - 15**	**0.6258**	**3.41**
8	20	10 – 11 - 19	9 - 15	0.7427	3.41
12	0.5	10 – 11	9	0.5877	3.57
12	10	10 – 11	9	0.4367	3.35
12	**20**	**10 -11-19**	**9 - 16**	**0.4169**	**3.60**
14	0.5	10 – 11-19	7-9	0.7517	3.01
14	10	10 - 11 - 19	6 – 9	0.6931	3.19
14	**20**	**10 - 11 - 19**	**6 - 13**	**0.6831**	**2.94**
17	0.5	10 – 11-19	9-16	0.7140	3.33
17	**10**	**10 - 11 - 19**	**6 – 9**	**0.6597**	**3.38**
17	20	10 - 11 - 19	9 - 13	0.7921	3.07

In the case of DG on node 12 with 20 MW, losses decrease by 49% in comparison with restoration without DG. The restoration process for this solution required closing lines 10, 11 and 19 and opening lines 9 and 16.

For the case of bus 8, the least losses occur for a power level of 10 MW, which represents a level of 26% of the total load and a total of 8 sectionalizers, closing 5 and opening 3 protective elements, which are on lines 10, 11, 19, 9 and 15.

In the case of bus 14, the penetration percentage that shows least losses (19.5%), in comparison with the 0.8494 MW of the fault without DG on bus 14, is through the opening of 1 sectionalizer element and the closing of 3; this case therefore has the least number of switch changes.

Best results from the simulations for each of the proposed cases are market with bold letter. In all configurations, there is an improvement in terms of losses, varying from 19.5% to 50.9% in comparison with a fault on line 2 without DG. We also observe that not necessarily the best restoration results are obtained with the highest levels of power injection.

An analysis based on the number of movements of protective elements shows that the best case is obtained with DG on bus 14, with only 4 movements, similar to the system without DG, followed by bus 12, with 5.

The above tests were repeated using a power factor of 0.85 in DG, which involves injection of active and reactive power by the generator (see Table 3). In general, losses are not reduced in all system tests, due to reactive power injection, since in many cases large flow reversals occur, which depends on the location and size of the available DG.

Table 3: Tests on Civanlar with DG with PF = 0.85, fault on line 2

DG on Bus	MW	Close Lines	Open Lines	Losses MW	T sec.
5	0.5	10-11	9	0.7082	3.48
5	10	10-11	9	0.6235	2.94
5	20	10-11-19	9-15	0.5885	3.58
8	0.5	10-11	9	0.6970	2.82
8	10	10-11-19	9-15	0.6532	3.55
8	20	10-11-19	9-13	0.8047	3.22
12	0.5	10-11	9	0.5904	2.90
12	10	10-11	9	0.4827	3.40
12	20	10-11	18	0.48930	3.40
14	0.5	10-11-19	7-9	0.72758	3.52
14	10	10-11-19	6-9	0.67153	3.19
14	20	10-11-19	6-9	0.75642	2.90
17	0.5	10-11-19	6-9	0.70223	3.35
17	10	10-11-19	6-9	0.67493	3.33
17	20	10-11-19	9-13	0.82961	3.44

4.2 Baran System

For the case of the Baran system, see Fig. 5, Table 4 shows the results without DG and with faults on different lines. These results show that, in order to isolate a fault on line 2, the sectionalizer elements located at the start of this line must be operated along with those at the start of lines 3 and 22, thus shutting down the power at node 3. By running the restoration algorithm it indicates the need to close the sectionalizer elements on lines 7, 9, 14, 32 and 37 and open those on lines 8, 30 and 34, leading to total losses of 0.6544 MW with a simulation time of 5.81 seconds. This new system topology gives 4.7 times the level of losses of the initial topology. As can be seen, this fault represents one of the worst scenarios for the system.

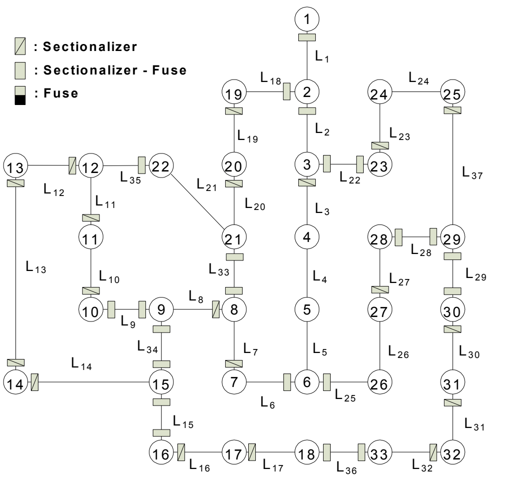

Fig. 5. Baran Power Distribution System

Table 4: Restoration for Baran System without DG

Fault online	Close Lines	Open Lines	Losses MW	Time sec.
2	7 9 14 32 37	8 30 34	0.6544	5.81
4	7 9 14 37	11 34	0.1563	4.75
13	14		0.1432	8.62
17	32 37	28	0.1351	7.06
18	7 9 32 37	28 35 36	0.1934	7.67

Table 5: Restoration for Baran System with DG, PF=1, Synchronized Mode

DG on Bus	MW	Close Lines	Open Lines	Losses MW	Time sec.
s/GD	**-**	**7-9-14-32-37**	**8-30-34**	**0.65445**	**5.81**
6	0.1	7-9-14-32-37	8-30-34	0.62412	6.00
6	1	7-9-14-32-37	8-30-34	0.41790	5.80
6	**3**	**7-32-37**	**30**	**0.25063**	**5.91**
14	0.1	7-9-14-32-37	8-30-34	0.62890	5.61
14	1	7-9-14-32-37	8-29-32	0.45136	6.36
14	**3**	**7-14-32-37**	**29-35**	**0.39422**	**6.13**
29	0.1	7-9-14-32-37	8-30-34	0.61494	6.39
29	1	7-14-32-37	30-34	0.37111	4.55
29	**3**	**7-32-37**	**16**	**0.23072**	**4.21**

Table 6: Restoration for Baran System with DG, PF = 0.85, Synchronized Mode

DG on Bus	MW	Close Lines	Open Lines	Losses MW	Time sec.
6	0.1	7-9-14-32-37	8-30-34	0.61044	6.09
6	1.0	7-14-32-37	30-34	0.32355	6.03
6	**3.0**	**7-9-32-37**	**10-31**	**0.09350**	**5.41**
14	0.1	7-9-14-32-37	8-30-34	0.61916	5.92
14	1.0	7-9-14-32-37	8-13-29	0.35029	6.09
14	**3.0**	**7-14-32-37**	**29-35**	**0.1919**	**5.53**
29	0.1	7-9-14-32-37	8-30-34	0.59652	4.57
29	1.0	7-9-14-32-37	8-31-34	0.25276	5.36
29	**3.0**	**7-9-32-37**	**10-13-34**	**0.03918**	**4.82**

In case of failure on line 2, the system is evaluated with the incorporation of DG on buses 6, 14 and 29, with power levels between 0.1 and 3 MW, representing levels of penetration of 67% and 80%, respectively. The results are shown in Table 5.

From the results it is possible to identify the dependence of the restoration process on the existence of DG in the system and also the level of power injected into the network. In cases where the power injection is small (100 kW), the restoration of the system under a fault on the line 2, is the same in all cases. However, for power injections of 1 and 3 MW the restoration is different and the power losses obtained depend on the configurations, the power injection and the locations of the DG nodes.

The simulations described above were performed again with reactive power injected into the system by the DG (operating with PF = 0.85), these results are shown in Table VIII. Comparing these results with those shown in Table 6 (PF = 1) it can be seen that the reactive power injection achieves further reductions in system losses.

4.3 Simultaneous Faults

In order to test the simplicity and speed with which the proposed algorithm is able to find the optimal topology for a restoration problem, simultaneous faults on the Baran system were also considered.

In addition to a fault on line 2, as analyzed above, a fault was also placed on line 15. As a result of this simultaneous fault, the simulation time is 8.63 seconds, proposing the closure of lines 7, 9, 14, 32 and 37 and opening line 8, 10, 27, 33 and 35. This new configuration has total power losses of 0.01675 MW. From these results it can be seen that simulation times are reduced from 12.69 (s) to 8.63 (s) corresponding to a decrease of 32%.

Moreover, for the Baran systems three simultaneous faults on lines 2, 15 and 11 was developed. Comparing the original configuration, the results show that the algorithm should close lines 7, 9, 14, 32 and 37, and open lines 8, 27 and 33 and that the three DG should operate in isolated mode. System losses are 0.017 MW and the simulation time is 3.63 (s), equivalent to a 58% reduction in time with respect to 2 simultaneous faults. This demonstrates the effectiveness of the algorithm against multiple failures

5. CONCLUSIONS

This study presents a service restoration model for minimizing power losses on a distribution system using Genetic Algorithms as the optimization technique. It makes use of the system's fundamental loop vectors, thus focusing the search for topologies that maintain the radial nature and connectivity of the system using nodes not exposed to the fault. This simplifies the restoration process, restricting the search space of possible solutions and even simplifying the problem in the case of multiple system faults, which makes the process search more efficiently and with reduced simulation time, as demonstrated in the tests performed.

Moreover, the model takes into account DG in order to determine the radial topologies that restore the system. The results have shown the dependence of the restoration process on the location and size of the DG nodes.

ACKNOWLEDGMENT

The authors gratefully acknowledge the National Committee for Research, Science and Technology (CONICYT) of Chile, for the financial support though Regular Fondecyt Project N° 1120178 and Fondecyt Initiation Project N° 11121437.

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