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Multi-fault service restoration in distribution networks considering the operating mode of distributed generation

Mendoza B. Jorge*, Vargas O. Héctor, López G. Miguel, Pavez D. Héctor

Escuela de Ingeniería Eléctrica, Pontificia Universidad Católica de Valparaíso, Valparaíso, P.O. Box 4059, Chile

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ABSTRACT

This article presents an electric power service restoration model for distribution networks considering distributed generation (DG). 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 with 17 and 33 buses. Results show the advantages of DG in the restoration process, the best operating mode of the DG and the effectiveness of the study technique.

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 [1].

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 favorable.

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 [2].

The main objective in restoring service is to reestablish the electric power service at the highest level of system load possible, through network reconfiguration without breaking operating conditions [3].

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. [4] is a bibliographic review that covers 1988–1994, while the article published by Adibi [3] covers 1981–1997, and finally, the work developed by Sudhakar and Srinivas [2] is a bibliographic review for the years 1988–2007.

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 [2].

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,

* Corresponding author. Tel.: +56 32 2273775; fax: +56 32 2273805.
E-mail addresses: jorge.mendoza@ucv.cl (M.B. Jorge), hector.vargas@ucv.cl (V.O. Héctor), miguel.lopez@ucv.cl (L.G. Miguel), hector.pavez@gmail.com (P.D. Héctor).

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mainly with the aim of decentralizing the restoration decision-making process [5–8].

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 [9], the fuzzy gray approach [10] and genetic algorithms [11].

As can be seen, there are many techniques and several different approaches to solving the service restoration problem. However, it is still necessary to continue developing new strategies that take into account new trends in distribution networks.

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 [12,13]. These DG networks can operate in two different ways during the restoration process. First, in operating jointly and in synchronism with the network [2] and secondly in isolated operation, creating a micro grid; see [6,14].

The present study develops a new electric power service restoration model for a medium voltage distribution network, taking into account the existence of DG and its optimal operating mode. The proposal uses GA as an optimization technique along with a loop vector system [15,16]. 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

Although literature shows that the problem has been solved from both multi-objective and mono-objective perspectives, this paper has considered that, even if the Pareto front solution of the multi-objective proposals is capable of delivering larger information about possible solutions, it requires a process of selecting alternatives from this front, which requires higher investment in time for decision making. Therefore, this proposal has chosen to program directly through a mono-objective given operator preferences. Moreover, even if the effect of the DG could be important on the system reliability, countries regulations and the IEEE Standard for Interconnecting Distributed Resources with Electric Power System do not allow DG island operation yet, especially in service concession models like the Chilean case. Therefore, the objective function considered in this study in order to maximize the restoration zone and minimize the distribution losses is defined as described below. In the case of 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):

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

Moreover, a set of the constraints is used to maintain correct operation of the network:

$$A \cdot i = I \quad (2)$$

$$i \le i_{\max} \quad (3)$$

$$v^{\min} \le v \le v^{\max} \quad (4)$$

$$M = N - N_f \quad (5)$$

where R_b is the “b” branch resistance; i_b is the “b” branch complex current; $i, i_{\max}$ is the current vector of branches and maximum current of branches; I is the vector of node currents; A is the incidence matrix; v is the node voltage; $v^{\min}$ is the node minimum voltage; $v^{\max}$ is the node maximum voltage; M is the radial net branch number; N is the node number; N_f is the source number; N_r is the total branch number.

Eq. (2) represents the node matrix of the current balance. Eq. (3) represents the thermal limit of the feeder and the maximum capacity of the substation. Eq. (4) considers the voltage restriction on each node, and Eq. (5) describes the restrictions on the radial nature of the primary distribution system. This proposal assumes that the technical aspects of the DG to control voltage and frequency for system synchronized operation or during island operation (for failure) are implemented, are reliable and meet the IEEE for Interconnecting Distributed Resources with Electric Power System Standard, which is applied to Chile.

3. Proposed solution

This study is based on the distribution network reconfiguration presented in [15], which uses genetic algorithms for optimization along with meshed network information vectors that efficiently guide the search for radial topology. GA is a heuristic optimization technique that has been applied to a variety of discrete and combinatorial optimization problems that do have advantages in finding the best solutions in front of other heuristic techniques.

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 [15,16] 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

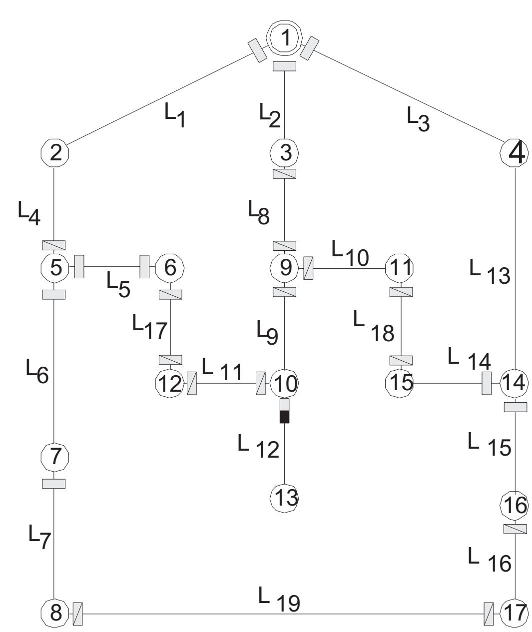

Fig. 1. IEEE 17 Civanlar power distribution system.