Electric Power Systems Research 110 (2014) 144–153

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Multi-Objective Evolutionary Algorithm for single and multiple fault service restoration in large-scale distribution systems

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ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form 17 January 2014
Accepted 21 January 2014
Available online 11 February 2014

Keywords:
Large-scale distribution system
Service restoration
Multiple faults
Node-Depth Encoding
Multi-Objective Evolutionary Algorithms

ABSTRACT

Network reconfiguration for service restoration (SR) in distribution systems is a complex optimization problem. For large-scale distribution systems, it is computationally hard to find adequate SR plans in real time since the problem is combinatorial and non-linear, involving several constraints and objectives. Two Multi-Objective Evolutionary Algorithms that use Node-Depth Encoding (NDE) have proved able to efficiently generate adequate SR plans for large distribution systems: (i) one of them is the hybridization of the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) with NDE, named NSGA-N; (ii) the other is a Multi-Objective Evolutionary Algorithm based on subpopulation tables that uses NDE, named MEAN. Further challenges are faced now, i.e. the design of SR plans for larger systems as good as those for relatively smaller ones and for multiple faults as good as those for one fault (single fault). In order to tackle both challenges, this paper proposes a method that results from the combination of NSGA-N, MEAN and a new heuristic. Such a heuristic focuses on the application of NDE operators to alarming network zones according to technical constraints. The method generates similar quality SR plans in distribution systems of significantly different sizes (from 3860 to 30,880 buses). Moreover, the number of switching operations required to implement the SR plans generated by the proposed method increases in a moderate way with the number of faults.

1. Introduction

Distribution system networks are generally structured in meshes, but operated in radial configuration for a better coordination of their protective schemes and reduction in the fault level [1]. Therefore, several distribution system problems, as service restoration (SR), which emerges after the faulted areas have been identified and isolated, usually involve network reconfiguration procedures [2,3].

Network reconfiguration is the process of altering the topological structure of distribution systems (DSs) by opening sectionalizing (normally-closed (NC)) switches and closing tie (normally-open (NO)) switches. When network reconfiguration is applied to the SR problem, the main objectives are to minimize both number of out-of-service areas and number of switching operations without violating the radiality and operational (limits for the node voltage, network loading, and substation loading) constraints.

Network reconfiguration for SR is a computationally complex problem, since it is (i) highly combinatorial, due to the large number of switching elements, (ii) nonlinear, since the equations governing the electrical system are in general nonlinear, (iii) non-differentiable, since a switch status change may result in crisp variations of values in objectives and constraints, (iv) constrained, due to the radiality and operational restrictions, and (v) multi-objective, since the SR plan should minimize the number of out-of-service areas and the number of switching operations.

Several methodologies have been investigated to design adequate SR plans based on heuristic algorithms [3], expert systems [4,5], data base [6], fuzzy reasoning [7] and meta-heuristics [8–12].

Abbreviations: CAO, Change Ancestor Operator; DS, distribution systems; MOEA, Multi-Objective Evolutionary Algorithm; MOP, Multi-Objective Problem; NDE, Node-Depth Encoding; NSGA-II, Non-Dominated Sorting Genetic Algorithm-II; NSGA-**N**, NSGA-II with NDE; MEA**N**, Multi-Objective Evolutionary Algorithm based on subpopulation tables and NDE; MEA**N**-M, MEA**N** with Multiple criteria tables; MEA**N**-MH, MEAN with Multiple-criteria tables and alarming Heuristic; MOEA/D, Multi-Objective Evolutionary Algorithm Based on Decomposition; NC, normally-closed; NO, normally-open; PAO, Preserve Ancestor Operator; SLFA, forward–backward Sweep Load Flow Algorithm; SR, service restoration; TPC, Taiwan Power Company; TSO, Terminal-Substation Order.

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http://dx.doi.org/10.1016/j.epsr.2014.01.017

The results achieved using meta-heuristics have been superior to the others in terms of number of switching operations and margins for operational constraints. However, most meta-heuristics for the SR problem demand long running time when applied to large scale DSs (DSs with thousands of buses and switches) modeled considering all their buses and switches [11].

In order to solve the SR problem for large-scale DSs, the selection of a subset of relevant switches for operation has been the strategy to avoid long running time (combinatorial explosion). However, using this strategy the number of feasible solutions (DS configurations attending all the technical constraints) becomes relatively small in relation to the number of feasible solutions when the same DS is modeled by a network considering all its switches. As a consequence, the modeling of a DS by a network with all its switches is more plausible (in this paper such a fact is evidenced by equivalent solutions obtained for larger DSs with number of switching operations lower than those obtained for smaller DSs). This complete modeling has been avoided in the literature since finding a feasible solution from such a model is computationally hard. In order to overcome this hurdle, the methods proposed in [2,13] combine Multi-Objective Evolutionary Algorithms (MOEAs) with the tree encoding named Node-Depth Encoding (NDE) [14].

As shown in [2,13], NDE can improve the performance of MOEAs in DS reconfiguration problems because of the following NDE properties: (i) NDE operators produce exclusively feasible configurations, i.e. radial configurations able to supply energy for the whole re-connectable system[1]; (ii) NDE can generate more feasible configurations in comparison to other encodings in the same running time since its average-time complexity is $O(\sqrt{n})$, where n is the number of graph nodes (each graph node corresponds to a DS sector[2]); and (iii) NDE-based formulation enables a more efficient forward–backward Sweep Load Flow Algorithm (SLFA) for DSs. Typically this type of load flow applied to radial networks requires a routine to sort network buses into the Terminal-Substation Order (TSO) before calculating the bus voltages [15]. Fortunately, the buses of each configuration produced by NDE operators are naturally arranged in the TSO, so that the SLFA can be improved by an NDE-based formulation.

The method proposed in [2], named MEA**N**, uses a technique of **M**ulti-objective **E**volutionary **A**lgorithm based on subpopulation tables with **N**DE. Each table stores the found solutions that better have met an objective or a constraint of the SR problem. On the other hand, the method proposed in [13] combines a modified version of the **N**on-**D**ominated **S**orting **G**enetic **A**lgorithm-II (NSGA-II) with **N**DE. This method is named NSGA-**N**. One of the main advantages of the NSGA-II is that it can properly deal with up to two objectives without weighting of them.

The MEA**N** [2] and NSGA-**N** [13] methods can generate adequate SR plans for large networks (networks modeling DSs with thousands of buses and switches). However, the SR plans for larger networks have not been as good as the ones obtained for smaller networks in terms of number of switching operations and margins for operational constraints. Moreover, the performances of those methods are degraded when applied to multiple faults, that is, the SR plans obtained for multiple faults are not as good as the ones obtained for a single fault.

A strategy to overcome those drawbacks is to combine the main characteristics of MEA**N** and NSGA-**N**. A preliminary investigation of such a type of combination was published in [16], in which the Pareto Front [17] and other fronts (evaluation criteria used by the NSGA-II) in the space of objectives are naturally aggregated in the method through the inclusion of new subpopulation tables in the MEA**N**. This paper extends such a principle of aggregating criteria to evaluate solutions by investigating additional types of subpopulation tables that benefit SR plans. Moreover, a heuristic is proposed to focus NDE operations on alarming network zones according to the technical constraints voltage drop and network loading. Both single and multiple faults are easily managed using the alarming heuristic since it can determine regions in the DS that actually require reconfigurations. All those improvements (aggregation of other criteria and the proposed alarming heuristic) are synthesized in a method called MEA**N** with Multiple-criteria tables and alarming Heuristic (MEA**N**-MH).

Results from the use of both relatively small (with 3860 buses) and large networks (with 30,880 buses) indicate that MEA**N**-MH can find SR plans for small networks as good as those for large ones (Table 4). Moreover, the quality of the best SR plans found considering multiple faults (from 2 to 8 faults) is comparable to the best SR plans found for single faults (Tables 6 and 7). Such a quality is measured through the margins obtained for each operational constraint (on average the voltage drop is kept in the 4.2–4.5% range for all multi-fault tests (Table 7)) and through the moderate increase in the number of switching operations in function of the number of simultaneous faults (Section 5.2.2).

This paper is organized as follows: Section 2 presents the formulation of the SR problem; Section 3 addresses SR for large-scale DSs, describing NDE and MOEAs for the SR problem; Section 4 proposes a new method (called MEA**N**-MH) based on MEA**N** and NSGA-**N** for dealing with large-scale DSs and multiple faults; Section 5 evaluates and compares MEA**N**-MH to the MEA**N** and NSGA-**N** methods; finally, Section 6 summarizes the main contributions and concludes the paper.

2. Formulation of the service restoration problem

The SR problem emerges after the faulted areas have been identified and isolated. Its solution is the minimal number of switching operations that results in a configuration with minimal number of out-of-service loads, without violating the DS operational and radiality constraints.

The SR problem can be formalized as follows:

$$\begin{aligned} &Min. \quad \phi(G) \quad and\ \psi(G, G^0) \\ &s.t. \\ &\qquad Ax = b \\ &\qquad X(G) \le 1 \\ &\qquad B(G) \le 1 \\ &\qquad V(G) \le 1 \\ &\qquad G \ \ is \ \ a \ \ forest, \end{aligned} \tag{1}$$

where G is a spanning forest of the graph representing a system configuration (each tree of the forest corresponds to either a feeder or an out-of-service area, nodes correspond to sectors and edges to switches), $\phi(G)$ is the number of consumers that are out-of-service in a configuration G (considering only the re-connectable system), $\psi(G, G^0)$ is the number of switching operations necessary to reach a given configuration G from the configuration just after the isolation of the faulted areas G^0, A is the incidence matrix of G, x is a vector of line current flow, b is a vector containing the load complex currents (constant) at buses with $b_i \le 0$ or the injected complex currents at buses with $b_i > 0$ (substation), $X(G)$ is the network loading of configuration G, that is, $X(G)$ is the max $(|x_j/\bar{x}_j|)$, where $\bar{x}_j$ is the upper bound of the current magnitude for each line current magnitude x_j on line j, $B(G)$ is the substation loading of configuration G, that is, $B(G)$ is the max $(|b_s/\bar{b}_s|)$, where $\bar{b}_s$ is the upper bound of the current

[1] The term "re-connectable system" means all out-of-service areas having at least one switch (NC or NO) linking them to energized areas. Some out-of-service areas may not have any switch to re-connect them to the remaining energized areas.

[2] A DS sector is a set of buses connected by lines without switches.