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Robust feeder reconfiguration in radial distribution networks

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ABSTRACT

Distribution feeder reconfiguration has been an active field of research for many years. Some recent theoretical studies have highlighted the importance of smart reconfiguration for the operating conditions of such radial networks. In general, this problem has been tackled using a multi-objective formulation with simplified assumptions, in which the uncertainties related to network components have been neglected by both mathematical models and solution techniques. These simplifications guide searches to apparent optima that may not perform optimally under realistic conditions. To circumvent this problem, we propose a method capable of performing interval computations and consider seasonal variability in load demands to identify robust configurations, which are those that have the best performance in the worst case scenario. Our proposal, named the Interval Multi-objective Evolutionary Algorithm for Distribution Feeder Reconfiguration (IMOEA-DFR), uses interval analysis to perform configuration assessment by considering the uncertainties in the power demanded by customers. Simulations performed in three cases on a 70-busbar system demonstrated the effectiveness of the IMOEA-DFR, which obtained robust configurations that are capable to keep such system working under significant load variations. Moreover, our approach achieved stable configurations that remained feasible over long periods of time not requiring additional reconfigurations. Our results reinforce the need to include load uncertainties when analyzing DFR under realistic conditions.

1. Introduction

Reconfiguration of radial distribution networks is a viable option for ensuring optimal or nearly optimal operation in the presence of several constraints and variable power demand [7,16,18–22,35]. From a theoretical perspective, distribution networks can always be reconfigured whenever imminent loading variations are detected. Even though optimization procedures may reveal improvements on power losses, voltage flatness or load balancing related to a given distribution network, it is important to realize that maneuvers performed by power utilities are still costly, lack appropriate equipment [35], and hence, they are unusual when such systems are operating normally. Although feeder reconfiguration seems to be very attractive to optimize the system's operating conditions, supervisory centers adopt a conservative strategy to avoid switching maneuvers as much as possible. This behavior can be justified by the low level of network automation and the imminent risks due to interference with protective devices, which may cause unexpected overloads or interruptions in the power supply. From the practical standpoint, maneuvers are the preferred procedure for solving critical or abnormal situations, but rarely for performance optimization.

Under normal conditions, seasonal variations in power demand require utility companies to rely on demand estimation models to properly meet demand within safety margins and quality indexes [4,6,16]. In these models, consumers are statistically classified according to their average demand [6]. Loading forecasts contain inherent errors because these approaches are based entirely on estimations. In addition, renewable energy has given its contribution to the power demand variation on load buses which originally acted as strict consumers. Its importance to the distribution systems may no longer to be neglected once the growing proportion of power generated by alternative means is intended to fill the gap between peak load demands and energy availability at regional extent [7].

A naive approach would treat network parameters as exact or definite values, and this approach could mistakenly assess a given configuration as optimal, adequate or fair to uncertainty-free environments. However, these configurations may be insufficient or even impracticable in the presence of power demand uncertainty.

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Nomenclature

N_B	bus set size	$\|\|X\|\|$	size of a given set $\boldsymbol{X}$
N_L	distribution line set size	$\|v\|$	modulus of the variable v
N_s	number of sources	$\Re$	set of real intervals
N_w	total number of switches	$[a]$	interval number
N_f	number of objective functions	$[\mathbf{a}]$	interval vector
N_v	number of uncertainty parameters	$\mathbf{a}^+$	upper bound of an interval vector
$\boldsymbol{x}$	binary vector containing all the switches statuses	$\mathbf{P}$	set of uncertainties
$\boldsymbol{x}^c$	cth configuration	$\boldsymbol{X}$	set of decision variables
$\boldsymbol{B}^s$	set of all buses supplied by source s	$\boldsymbol{p}$	vector of uncertainty parameters
Z_i	impedance of the ith distribution line	$\boldsymbol{f}$	vector of objective functions
I_i	current flow in the ith distribution line	$\boldsymbol{g}$	vector of inequality constraints
$I_i^{\max}$	ampacity (maximum current) of the ith distribution line	$\boldsymbol{h}$	vector of equality constraints
V_k	actual voltage at bus k		
V_k^{nom}	nominal or normalized (p.u.) voltage at bus k		

Hence, it is important to obtain robust solutions. In our approach, robust solutions are those solutions that are less susceptible to uncertainties and they are able to maintain a system normally operating even in the worst case scenario. In this work, we restricted uncertainties to PQ loads, because they are among the most relevant factors in feeder reconfiguration decisions, mainly if we consider power generation in those buses [12,32–34]. Because feeder reconfiguration depends on some power flow method [2], uncertainties must be accounted for using a mathematical model capable of reflecting all immediate effects on the power flow [11,12,32,33].

Feeder reconfiguration is considered a combinatorial problem with an irregular search space [26,31] and is generally formulated as a restricted multi-objective problem. The radiality constraint and the discrete nature of the switches prevent the use of classical techniques to solve feeder reconfiguration [2,18,19,23,25,27]. An evolutionary stochastic approach was chosen because this approach is relatively unaffected by the nature of the problem. As previously mentioned, an efficient solution set in a deterministic environment can be partially or totally impaired in a perturbed environment, which moves these solutions away from the Pareto frontier [14]. Thus, a conventional approach will probably fail to identify an efficient solution set to the feeder reconfiguration problem. Therefore, we present a proper implementation, in which a Multi-Objective Evolutionary Algorithm (MOEA) based on NSGA-II [13] was coupled to an interval version of the Backward/Forward Sweep Method (BFSM). This novel hybrid approach, which we call Interval Multi-objective Evolutionary Algorithm for Distribution Feeder Reconfiguration (IMOEA-DFR), is a robust method of solving reconfiguration problems. To our knowledge, there is no study encompassing this specific issue yet. The objectives of this work are (i) to provide a new strategy that properly addresses load uncertainties in DFR optimization (see Section 5), (ii) to demonstrate the fragility of optimal solutions found by conventional approaches in uncertain real-world environments (see case 2 in Section 6), and (iii) to discuss how robust solutions can replace pseudo-optimal solutions to ensure reasonable and satisfactory network operating conditions in the worst case scenario (see case 3 in Section 6).

This paper is organized as follows. In Section 2, related works are cited, and their primary contributions are highlighted. The formulation of the DFR problem is presented in Section 3. In Section 4, the background of interval analysis is addressed, and the robust version of the DFR problem is defined. The implemented algorithm and related issues are described in Section 5. Finally, a discussion about computational experiments is presented in Section 6, and concluding remarks are given in Section 7.

2. Related works

The feeder reconfiguration has been treated as a typical uncertainty-free problem in many papers [2,3,7–10,15,25,26,29]. From a classical perspective, these approaches are satisfactory, and their solution sets are valid whenever uncertainties are negligible. However, these solutions are not as reliable as they seem [5]. It has been shown that electrical power systems are subjected to many sources of uncertainty such as power (load) demand [16,20–22], distributed generation [21,22], and electrical parameters [5,6,35].

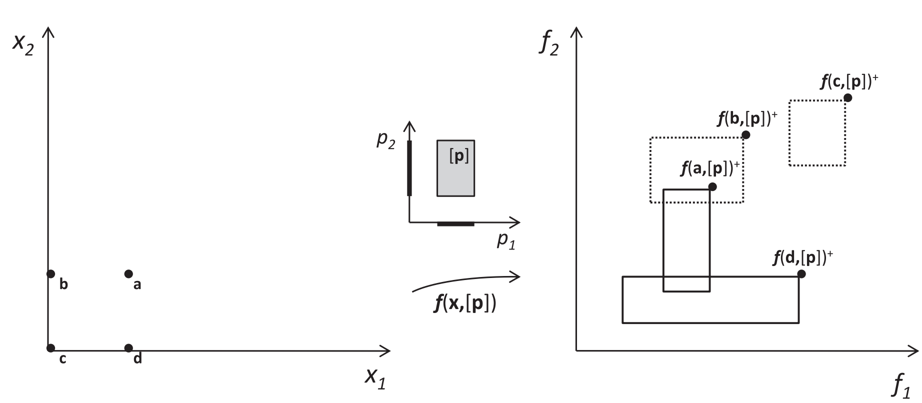

Fig. 1. Computation of the worst case performance for some solutions in the decision variable space – 2D example.