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Optimal reconfiguration of distribution systems with representation of uncertainties through interval analysis

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ABSTRACT

The present work presents an approach for optimal reconfiguration of electrical distribution systems (EDS) to minimize energy losses considering uncertainties in the load demand and in the wind based distributed generation (DG). The optimization algorithm applied to solve the reconfiguration problem is based on the bio-inspired metaheuristic Artificial Immune Systems (AIS). An interval power flow model is used to obtain an interval energy loss from the representation of the uncertainties. The interval loss is used to guide the AIS algorithm through the search space. Network and operational constraints as the radiality and connectivity of the network as well as different load levels are considered. Well-known test systems are used to assess the impact of the uncertainties representation in the reconfiguration problem.

Introduction

Nowadays, there is a constant search for efficiency in any productive sector. This requirement is also pursued in the electricity distribution sector. In this context, the minimization of energy losses in electrical distribution systems is important, since the technical loss is one of the main reasons for increasing the system operating costs [1]. A widely explored alternative in the literature to reduce energy losses is the reconfiguration of the distribution network [2–4]. Reconfiguration consists in determining a radial and connected network topology that optimizes the operational state by, for instance, reducing the technical losses and meeting the system constraints [3].

In most studies on reconfiguration of distribution networks, the power flow used for evaluation of each candidate solution is deterministic in nature, which is mainly because the analysis is limited to a single particular point in time and the control variables are fixed. However, the actual load demand of an EDS has a degree of uncertainty due primarily to errors in measurement and constant load variation [5,6]. There are also uncertainties related to distributed generation based on renewable sources as the wind based generation [7,8]. Therefore, the introduction of such uncertainties in power flow to analyze an EDS state leads to a more realistic representation. The uncertainties can be represented by using interval mathematics [5,6].

Probabilistic analysis has been performed in the literature to represent the uncertainties related to power systems. A probabilistic DC load flow is proposed in [6] that considers the power injections at the load busbars as random variables and determines density probability functions for the power flows in the branches. A current injection power flow model based on the interval arithmetic is proposed in [9] for including the uncertainties over the load demand in the system analysis. In [10], a discrete convolution technique in the frequency domain is applied to solve a probabilistic power flow.

Approaches for reconfiguration of EDS with the representation of uncertainties have been proposed [7,11–13]. In [7], a probabilistic model is proposed to represent the uncertainties related to diary load variation and distributed generation. The operational conditions of DG sources are considered with the respective probabilities in the reconfiguration problem that is solved by a genetic algorithm. In [11], it is proposed a methodology for EDS reconfiguration to improve the system reliability. Probabilistic models are used to assess the reliability at the load busbars. The optimization method for the reconfiguration is based on integer programming and the metaheuristic known as particle swarm optimization.

In [12], a fuzzy probabilistic model that combines fuzzy logic and Monte Carlo technique is presented to include uncertainties in the reconfiguration problem for energy loss minimization. The approach considers statistical failure and repair data of the distribution system components. The reconfiguration for each system state is done by applying a logic programming algorithm and the system states are obtained by Monte Carlo simulation. Fuzzy logic are also used in [13] for EDS reconfiguration and load balancing to

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improve the system load profiles. The fuzzy system generates the initial set of configurations for a genetic algorithm. A probabilistic model is used to represent the voltages uncertainties due to demand variation that allows identifying the most sensitive load busbars.

In [8], it is proposed a methodology for distribution networks expansion planning including the penetration of distributed generation with the investment in new equipments, reconfiguration and restoration plans. A multiple scenario model is presented that considers uncertainties related to the loads and the power from DG units. The model is based on the theory of pseudo-dynamic programming. A genetic algorithm solves the combinatorial optimization problem.

An interval analysis for a multi-objective EDS reconfiguration problem that aims at minimizing the losses and optimizing the system reliability indexes is proposed in [14]. The interval analysis is proposed to handles the imprecision and uncertainties related to the reliability indexes, the system parameters and the load data. The interval analysis allows quantifying the impact of such uncertainties in the optimization problem, which is solved by a local search heuristic technique.

The optimal reconfiguration of EDS to minimize energy losses is a problem of nonlinear mixed integer programming that is combinatorial in nature and whose search space is not convex [4]. The radial and connectivity constraints make this problem even more complex. The only way to ensure that the global optimal solution will be obtained for such a problem is to assess all possible combinations, which is computationally unsuitable for the requirements of EDS [4]. From such aspects, metaheuristics can be applied to the reconfiguration problem because they can efficiently analyze the huge search space. In [3], the metaheuristic known as Artificial Immune Systems is applied to reconfigure distribution networks aiming at minimizing technical losses. A deterministic power flow is used to evaluate each candidate topology in the AIS algorithm.

The present work presents an approach for reconfiguration of electrical distribution systems based on the bio-inspired metaheuristic AIS that considers uncertainties in the load demand and in the wind based distributed generation. The objective is to minimize the total energy loss comprising different load levels in a more realistic representation of the load and DG. The AIS algorithm has efficient evolutionary mechanisms for covering the search space [3,15]. The interval mathematics fundamentals are embedded in an interval power flow that models the uncertainties. The input interval variables are the active and reactive load demands and the wind speed. The uncertainties are thus propagated to the output power flow variables as the nodal voltages [9]. As a result, the total energy loss to be minimized is also given in interval form. A methodology for comparing intervals that is based on the interval midpoint and radius [16] is used to determine the best topology among the candidate configurations of the AIS algorithm. The network constraints as radiality and connectivity are met by applying graph theory concepts and by the AIS evolution mechanisms. The main contribution is the application of interval mathematics for assessing the impact of representing uncertainties in the reconfiguration of EDS, by using an optimization algorithm untapped for this purpose. The proposed approach is tested in four systems from literature.

Interval power flow

Algorithm and formulation

The interval power flow can determine the state variables of an electrical power system considering uncertainties over such parameters as the load and generation. The present work uses the Newton power flow method in polar coordinates and the interval model is based on the Krawczyk method, which is an efficient technique for solving nonlinear interval systems [17] and stems from Newton method [9]. Fig. 1 shows the steps of the interval power flow that are described hereafter.

Step 1: The nodal voltages obtained from a deterministic power flow are used as starting point for the interval power flow and are considered as the midpoints of the initial interval voltages.

Step 2: Determines the percent variation of the load demand and the wind based DG as in (1)–(4).

$$Pd_k^i = [Pd_k^d \cdot (1 - \alpha_{pkl});\ Pd_k^d \cdot (1 + \alpha_{pku})] \quad (1)$$

$$Qd_k^i = [Qd_k^d \cdot (1 - \alpha_{Qkl});\ Qd_k^d \cdot (1 + \alpha_{Qku})] \quad (2)$$

$$Pwt_k^i = [Pwt^{inf};\ Pwt^{sup}] \quad (3)$$

$$Qwt_k^i = [Qwt^{inf};\ Qwt^{sup}] \quad (4)$$

where Pd_k^i and Pd_k^d are the interval and deterministic active load demand at busbar k, respectively; Qd_k^i and Qd_k^d are the respective reactive load demands; α_{pkl}, α_{pku}, α_{Qkl} and α_{Qku} are load demand percent variations; Pwt_k^i, Pwt^{inf} and Pwt^{sup} are the interval and the lower and upper limits of the active power from a wind generator at busbar k, which are given as a function of the wind speed

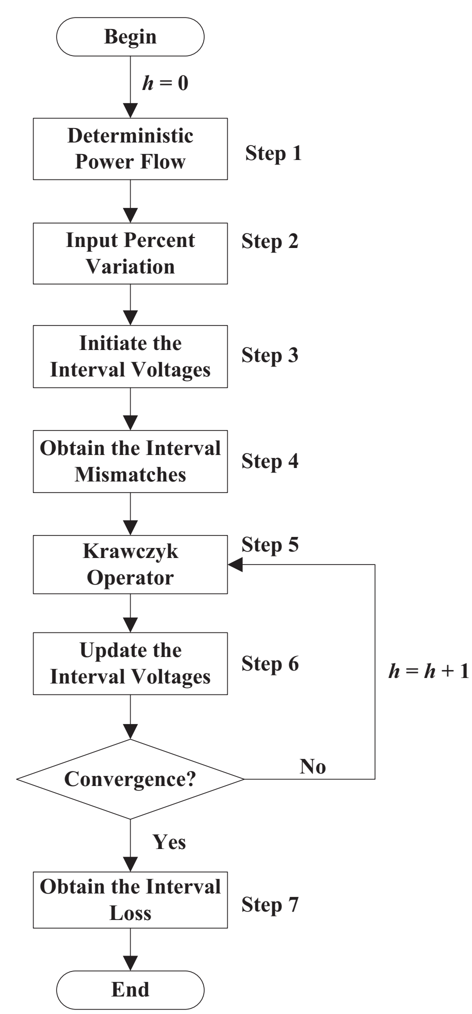

Fig. 1. Flowchart of the interval power flow algorithm.