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Optimal reconfiguration of electrical distribution systems considering reliability indices improvement

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ABSTRACT

This paper presents a mixed-integer second-order conic programming (MISOCP) model to solve the reconfiguration problem of electrical distribution systems, considering the simultaneous minimization of total active power losses and improvement of customer-oriented reliability indices. The reliability indices considered in this paper are the system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI), and the energy not supplied (ENS). Under radiality, the proposed model satisfies the operational constraints of the reconfiguration problem, i.e., the voltage magnitude limits of the nodes and the current capacities of the conductors are not violated. The use of an MISOCP model guarantees convergence to optimality via convex optimization software tools. A multi-objective optimization approach is used to generate a full Pareto front surface that shows the conflict between the active power loss minimization and the improvement of the reliability indices in the reconfiguration problem. Finally, in order to test and verify the proposed methodology, a 43-node test system and a real 136-node system were employed.

Introduction

Recent developments in telecommunication technologies, automation, and digital signal processing form the framework of a smart distribution grid. In this context, the switching and protecting devices located along the feeders can be remotely supervised and controlled, enabling the system to respond quickly to contingencies by deploying an automated restoration scheme that minimizes the unsupplied demand [1]. However, switching devices can also be used to optimize the steady-state operating point of the system under normal conditions. Switch operation affects the electrical behavior of the system by changing a feeder's topology. Thus, network operators can use switching devices to reduce active power losses, to balance load flow through the feeders, and to regulate the system's voltage magnitudes in response to changes in demand or generation. These are the classical aims of the reconfiguration problem of electrical distribution systems (EDS). Reference [2] presents an extensive survey of network reconfiguration methodologies up to 2013.

The main reason for distribution utilities to invest in switching and protecting devices is to prevent prolonged failures and to reduce the number of customers isolated by faults. Outages diminish the quality of service and compromise the physical infrastructure of the system. Therefore, it is important to effectively measure and prevent such failures. The measurement of a network's capacity to maintain steady-state operation continuity over a defined period of time can be estimated using reliability indices. The most common indices used by utilities around the world are the system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI), and the energy not supplied (ENS) [3,4]. With this in mind, utilities install protection/maneuver devices in the networks to create load zones that, depending on their level of selectivity and coordination, can properly isolate most long-term faults and reduce the number of unattended customers. This scheme maintains the reliability indices below the limits imposed by system regulators, and utilities are not forced to compensate their users for poor quality service [5].

Some works analyzing the optimal reconfiguration of EDS considering reliability improvement can be found in the specialized literature. Despite the various strategies used by different authors to estimate the interruption frequency and duration at each load point, most of the optimization techniques have been based on heuristic or metaheuristic algorithms due to the non-linear and combinatorial nature of the problem. These methodologies have usually employed a multi-objective approach to deal with the conflict between power loss reduction and reliability improvement in

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the objective function. Thus, evolutionary techniques [6,7] and fuzzy logic algorithms [8] have been successfully applied to provide quality solutions to the problem. More recently, new, interesting algorithms have been proposed [9–11], and new characteristics have been appended to the model, such as stochastic optimization [12] and distributed generation (DG) impact [13]. Methods commonly used to estimate the reliability indices have been based on Monte Carlo simulations and graph search algorithms due to the stochastic nature of component failure rates and the radial topology of the networks [14].

This paper presents a mixed-integer second order conic programming (MISOCP) model for the optimal reconfiguration of EDS considering reliability indices improvement. Each switch status (open or closed) represents the main binary decision variable of the MISOCP model. The proposed model aims to determine a system topology that minimizes the active power losses and reduces the average annual service interruption, average annual interruption duration, and total energy not supplied in a year. Together with the electrical bus and branch parameters of the EDS, the proposed model employs historical data or predictive expected values of all component failures and restoration rates, in order to assess the average reliability indices of the system [15]. Finally, the proposed model considers the operation of fuses and selectivity among switches. The use of an MISOCP model guarantees optimality by using existing convex optimization tools. A multi-objective optimization approach is used to visualize all non-dominated solutions and to construct a full Pareto front surface, which compares the active power losses against the two main reliability indices, SAIDI and SAIFI. The proposed model was implemented using the mathematical programming language AMPL [16], and solutions were found via the commercial optimization solver CPLEX [17]. A 43-node test system and a real 136-node distribution system were used to demonstrate the accuracy of the proposed mathematical approach, as well as the performance of the proposed solution technique.

The main contributions of this paper are as follows:

1. A novel MISOCP model for solving the reconfiguration problem of EDS considering reliability indices improvement.
2. An MISOCP formulation for the reconfiguration problem with the following benefits: (a) a flexible, realistic, and precise model; (b) efficient computational behavior with conventional MISOCP solvers; and (c) a convergence to optimality guaranteed by using convex optimization techniques.
3. A multi-objective optimization approach used to obtain the full Pareto front surface of the reconfiguration problem considering two different objective functions (active power losses and customer-oriented reliability indices).

Mathematical model for the optimal reconfiguration of EDS considering reliability indices improvement

Assumptions

The analytical expressions used to calculate the steady-state operation of the EDS are based on the mathematical representation normally used in backward/forward sweep load flow algorithms [18,19], and developed according to the following assumptions:

1. Electrical loads in the EDS are modeled as constant active and reactive power loads at every node.
2. The system is balanced and represented by its single-phase equivalent circuit.
3. Switches are very short-length circuits with negligible impedance.

The above assumptions are illustrated in Fig. 1, where, $\vec{V}_i$ and $\vec{I}_{ki}$ are the phasors of the voltage at node i and the current through branch ki, respectively. Also, $R_{ki}I_{ki}^2$ and $X_{ki}I_{ki}^2$ are the real and reactive power losses of branch ki respectively, concentrated at node i. If the branch is either a switch or a breaker, as with branch ij in Fig. 1, the branch variables are marked with the superscript "sw" and losses are disregarded.

Mathematical model for the reconfiguration problem of EDS

The reconfiguration of the EDS is an operational planning problem in which the switches allocated along the feeders are operated with the aim of reducing the total active power losses. Meanwhile, there are technical and operational constraints that system controllers have to consider when modifying the EDS. These constraints are voltage deviation limits, current flow limits through branches, substation capacities, and radial operation. Radiality is an operational constraint that utilities impose for technical reasons, such as to simplify protection schemes and voltage regulation, and to reduce short-circuit currents.

The mathematical model for the EDS reconfiguration problem considering radiality constraints and switch/breaker operation is shown in (1)–(13). It has been adapted from the mathematical model proposed in [20]. The current flow magnitude and voltage magnitude appear naturally as squared variables, hence it is convenient to consider the following change in variables: $I_{ij}^{\text{sqr}} = I_{ij}^2$, $I_{ij}^{\text{sw,sqr}} = \left(I_{ij}^{\text{sw}}\right)^2$, and $V_i^{\text{sqr}} = V_i^2$.

$$\min \; c^{\text{lss}} \sum_{ij \in \Omega_l} R_{ij} I_{ij}^{\text{sqr}} \tag{1}$$

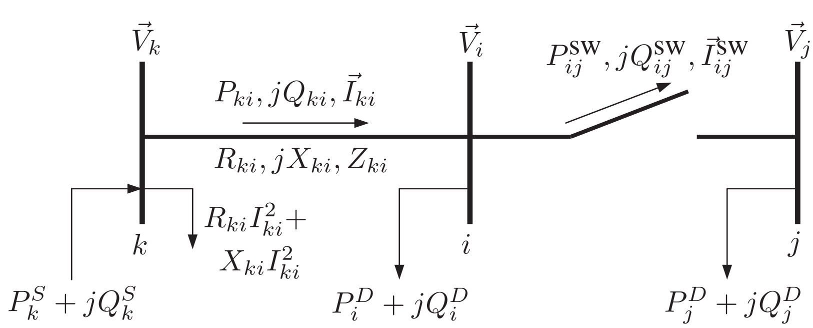

Fig. 1. Radial EDS analysis.