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Real-time smart distribution system reconfiguration using complementarity

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ABSTRACT

Smart Radial Distribution Systems (SRDS) of the future will have improved reliability, performance and flexibility in operation by using algorithms such as optimal reconfiguration in real-time in their distribution management systems. However, today, optimal reconfiguration algorithms are largely academic because of challenges such as they (1) depend upon heuristic techniques that require repeated runs and are not suitable for real-time applications, (2) do not guarantee an optimal solution and, (3) do not provide insight into solution space.

In order to realize SRDS of the future, a real-time optimal reconfiguration algorithm is proposed, which uses a classic nonlinear optimization technique and guarantees an optimal solution in the least time. The method is based upon a complementarity technique that transforms discontinuous solution spaces into continuous, enabling use of classical nonlinear optimization techniques without resorting to heuristics.

Using the complementarity technique, a nonlinear optimization formulation and classical solution method is needed to optimally reconfigure a SRDS and to minimize losses while obtaining an acceptable voltage solution is proposed.

This is successfully demonstrated on 7-bus, 33-bus, and 69-bus distribution systems and the results are compared with those available in literature with respect to solution time, accuracy in results and robustness of the proposed algorithm and demonstrate superiority of the proposed technique.

1. Introduction

SMART radial distribution system (SRDS) of the future will provide improved performance, reliability, and flexibility to best connect new elements such as renewable generators, energy storage, electric vehicles, etc. SRDS using a distribution management system (DMS) will be able to optimally reconfigure the system in real-time to improve performance and provide a highly reliable service. In a future setting, SRDS would have breakers and switches that are remotely controlled via DMS taking optimal settings from the optimal reconfiguration algorithm. It is necessary to have optimal reconfiguration algorithms that can function in real-time to benefit from the SRDS infrastructure. It is also necessary to develop optimal reconfiguration algorithms that are reliable and efficient which do not depend upon heuristics.

Electric utilities may reconfigure their network such that total system losses are minimized and voltage profile is satisfactory.

Optimal reconfiguration requires that one breaker or tie switch in every loop is opened, such that the set of closed breakers result in a radial topology, which result in minimum losses and a satisfactory voltage profile. An optimization algorithm for optimal reconfiguration shall consider all possible combinations and scenarios of where one switch can be opened in every loop. This problem is a combinatorial challenge and its complexity increases exponentially with the number of switches. Further, examining the solution domain, which is undertaken in the next section, it is evident that the solution space is discontinuous.

Literature review shows that many researchers have attempted different optimization techniques and have found the optimal solution for published examples. However, limitations in classical linear and nonlinear optimization techniques preclude them from being successfully used for this optimization challenge. Hitherto, all attempts are restricted to optimizing using heuristic techniques such as evolutionary programming, genetic algorithms, etc.

Several methods [1–16] have been utilized in an effort to solve this mixed-integer non-linear program using genetic algorithms.

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Nomenclature

ΨM	diagonal matrix with continuous elements corresponding to switches status
ΨM_i, ΨM_j	elements of ΨM corresponding to the status of switches *i* and *j, respectively*
F_B	from bus, represents the sending end
M	penalty factor
N	number of switches in each loop
N_B	number of buses
N_L	Number of lines
N_S	Number of loops
$N_S(s)$	set of line indices comprising the *s*th loop
P_D and Q_D	vectors of bus-wise real and reactive power loads
P_G and Q_G	vectors of bus-wise real and reactive power generations
P_i and Q_i	net real and reactive power injected by the *i*th bus into connected lines line real-power loss
P_L	total system real-power loss
T_B	to bus, represents the receiving end
$V\angle\delta$	vector of bus voltage phasors
$\underline{V}$, $\overline{V}$	lower and upper bus voltage magnitude limits
Y_B (Y-BUS)	system admittance matrix
[*YI*]	bus incidence matrix
[*YL*]	diagonal matrix of line admittance values

[1] and [2] have been successful in finding an optimal solution using fuzzy genetic and harmony search algorithms. A fuzzy controlled real coded genetic algorithm was used in [3] to solve the reconfiguration problem. Two controllers had been used to adaptively adjust the crossover and mutation probabilities based on the fitness function. An efficient codification to solve the distribution network reconfiguration for the loss reduction problem is reported in [4]; however, they are still using evolutionary algorithms and are not benefiting from using a regular NLP. Mendes et al. [5] used evolutionary algorithm to address the particular case of reconfiguration after an outage caused by the loss of a single branch of the network. The work in [6] claims that a multi-objective evolutionary algorithm (EA) based on subpopulation tables adequately models several objectives and constraints, enabling a better exploration of the search space. Ref. [7] presents a novel charged system search (CSS) algorithm, the particle moving evaluation mechanism CSS (PMEM-CSS), for determining the switching strategy in order to solve the distribution system loss minimization problems. In [8], a novel optimization method that provides an error bound on the solution quality is found. Thus, the obtained solution quality can be evaluated in comparison to the global optimal solution. Instead of using local updates, a highly compressed search space is constructed using a binary decision diagram, and the optimization problem is reduced to a shortest path-finding problem.

A non-revisiting genetic algorithm (NrGA) is used to determine distribution network configuration for loss reduction [9]. By advocating binary space partitioning (BSP) to divide the search space and employing a novel BSP tree archive to store all the solutions that have been explored before, a new solution is generated by genetic algorithms (GA), and can mutate an alternative unvisited solution. The main contribution of [10] is the presentation of GA with two network encodings, capable of representing only radial connected solutions without demanding a planar topology or any specific genetic operator. In [11], the GA was successfully applied to the loss minimization reconfiguration problem. In the proposed algorithm, strings consist of sectionalizing switch status or radial configurations, and the fitness function represents the total system losses and penalty value for voltage drop and current capacity violations. In [12], an effective approach based on the particle swarm optimization with integer coded is presented to determine the switch operation schemes for feeder reconfiguration. Fuzzy adaptation of evolutionary programming has been also implemented [13]. Ant colony search-based loss minimization for reconfiguration of distribution systems is used in [14]. In [15], the same problem is solved using GA. In order to enhance its ability to explore the solution space, efficient genetic operators are developed.

The algorithm in [16] is based on a heuristic rule and fuzzy multi-objective approach and it has been tested on a 69-bus system to solve the network reconfiguration problem. While the work reported in literature has found optimal solutions, evolutionary computations, and genetic algorithms were always used due to the zero-one state nature of switches. The solution space is always discontinuous and do not derive benefits of a typical optimal power flow algorithm. Some of the disadvantages of using such techniques are explained in [17] and [18]. In [19], the problem of reconfiguration of distribution systems considering the presence of distributed generation is modeled as a mixed-integer linear programming (MILP) problem. It was possible to create a robust mathematical model that is equivalent to the mixed-integer non-linear programming model, and guarantees convergence to optimality using classical optimization techniques. The routine is tested and validated on real power system.

In summary, there is no guarantee for finding optimal solutions in a finite amount of time when using GA. In addition, parameter tuning is mostly accomplished by trial-and-error and there is no absolute assurance that GA will find a global optimum at all. One of the other disadvantages of GA is that it cannot assure constant optimization response time. Furthermore, the difference between the shortest and longest optimization response time is much larger than with conventional optimization methods. Such property limits the practicality of these techniques in real-time applications. In general, GA and artificial intelligence techniques are valuable only for offline solutions or when no other classical method is available. Hence, it is evident that use of current optimal reconfiguration algorithms for SRDS in DMS is not possible and requires new technique amenable for real-time applications.

In this work, in search of making optimal reconfiguration suitable for real-time use, recent work on complementarity [20] and [21] is utilized. Using complementarity, the nonlinear mixed integer optimization challenge of optimal reconfiguration with discontinuous solution space is transformed into a nonlinear optimization challenge with continuous solution space. This transformation allows the use of classical nonlinear optimization solvers that are robust, guaranteeing the best solution while being suitable for real-time application.

Accordingly, in this paper, the authors propose to use complementarity constraints and transform the solution space such that conventional NLP techniques can be used for solving the challenge of optimal reconfiguration of SRDS in real-time. In [22], complementarity technique is employed to reconfigure power distribution systems. The routine is applied only to a small-size system with one loop.

2. Complementarity

Consider example is shown in the problem (P1) with the following objective function:

$$\text{Maximize}\,(3x_1 - 2)^3 + (5x_2 - 1)^3 \tag{1}$$

Subject to:

$$0 \le x_i \le 1 \quad \forall i = 1, 2 \tag{2}$$

$$x_1 x_2 = 0 \tag{3}$$