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Combined heuristic with fuzzy system to transmission system expansion planning☆

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ABSTRACT

A heuristic algorithm that employs fuzzy logic is proposed to the power system transmission expansion planning problem. The algorithm is based on the divide to conquer strategy, which is controlled by the fuzzy system. The algorithm provides high quality solutions with the use of fuzzy decision making, which is based on nondeterministic criteria to guide the search. The fuzzy system provides a self-adjusting mechanism that eliminates the manual adjustment of parameters to each system being solved.

1. Introduction

The transmission system expansion planning is a classical problem in the power systems. A well conducted planning of the transmission system should be carried out periodically according to the changes on generation and demand scenarios. The way the power system is hierarchically organised and how it is operated should be considered for the mathematical modelling, which must be tailored for each reality. The fundamental model for this problem is represented by the decision making, among several choices, on the location and also on the number of transmission lines that must be installed to satisfy the desired operating conditions. In the model considered in this study, the decision making is centralised and the expansion must satisfy a single time period. This model is also known as centralised static planning. More general models have more time periods, as a consequence, the moment to make the investment also becomes a variable. The latter case is known as centralised multi-period planning [1].

Even with the simplest model, the problem represents a highly complex mixed integer nonlinear problem (MINLP). Various methods have been proposed for its resolution. For example, the classical optimisation methods such as Benders decomposition and branch-and-bound based methods [2]. Other methods such as the constructive heuristics [3–5]; meta-heuristics, have also been applied successfully to the transmission system expansion problem and they have achieved the best solutions so far. Some of the most used meta-heuristics are: Tabu search [6], genetic algorithm [7], simulated annealing [8] and GRASP [9].

1.1. Rationale

This work revisits the constructive heuristic algorithm with the objective to improve the performance of this class of method. A constructive heuristic is a method that is based on specific criteria, "constructs" the solution iteratively and stops when a feasible solution is found. Although limited when compared to meta-heuristics, its development has significant importance because of its versatility and usability as a tool for rapid generation of feasible topologies, or for meta-heuristics to provide feasible configurations as starting points (or populations). As a consequence, the development of good heuristics may lead to more efficient meta-heuristic algorithms.

The majority of the constructive heuristics is based on sensitivity indices (SI). The objective of these indices is to represent, numerically, the circuit performance according to the topology. In [1], some of the major shortcomings that result in the premature convergence (usually at low quality solutions) have been addressed. Most of the constructive algorithms performs a greedy search, which rarely result in good solutions for realistic systems. In this paper, we propose an algorithm that deals with not only the deficiencies of the constructive algorithms but also makes the heuristic more flexible. In [10], a constructive heuristic algorithm has been modified based on the branch-and-bound algorithm and it has presented good performance, however, the best solutions are

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only obtained after the careful setting of parameters for each system. In this work, the constructive heuristic algorithm is enhanced in two aspects: it is combined with the fuzzy system in order to incorporate intelligent search, which makes it more intelligent than other algorithms. Moreover, it keeps the basic aspects of the constructive heuristic algorithm such as: simplicity and fast convergence. The main objective is to develop an efficient yet simple algorithm.

Several research papers considering fuzzy systems for transmission expansion planning have been published. In [11], fuzzy decision making is used for selection of the topologies generated by multi-objective genetic algorithm. The objectives are to enhance investment costs, security and environmental impact. In [12], the transmission system expansion planning (TEP) problem is modelled as an integer-fuzzy programming problem and the investment and security conditions are taken into account. Differently from other similar approaches, here the fuzzy system is part of the constructive heuristic algorithm, whose main objective is to lead the search to high quality solutions without being affected by premature convergence to poor local optima. The structure of this paper is as follows: In Section 2, the mathematical model of TEP problem is introduced; in Section 3, the constructive algorithm with fuzzy system is shown. In Section 4, the tests and results with the proposed method are presented, a discussion on the results are presented in Section 5 and in Section 6 the conclusions are drawn.

2. The mathematical model

It is possible to employ different mathematical models to solve the transmission system expansion problem (TEP) [13]. Some of them are more comprehensive than others, and they depend on the objectives of the planning. For example, it is possible to include loss minimisation [14], reliability evaluation or $(n-1)$ [15] security criterion in a multi-objective formulation. However, such broad analysis must be performed carefully due to the uncertainties on the scenarios and also because of increase in the computational burden.

In this work, the single period long-term planning, which determines only the necessary transmission lines in a single planning horizon and for a given load growth estimate, is solved. The expansion problem is modelled as a mixed-integer nonlinear problem, and its formulation is based on [5]. On the one hand, for a long-term planning the main concern is the bulk power transfer to the load centers. In this case, some requirements such as voltage constraints may not be considered. On the other hand, in a short-term planning, operation details must be taken into account, for instance, it is important to manage the reactive power and many other operation and security constraints. In the latter case, the AC model [16] would be preferred. In next section, the DC model, which has been used as the reference model for long-term planning will be presented.

2.1. DC model

The single period minimum cost DC model can be formulated as follows:

$$Min \quad v = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} \quad (1)$$

s.t.

$$Sf + g = d \quad (2)$$

$$f_{ij} - \gamma_{ij}(n_{ij}^{o} + n_{ij})(\theta_i - \theta_j) = 0 \quad (3)$$

$$|f_{ij}| \le (n_{ij}^{o} + n_{ij})\bar{f}_{ij} \quad (4)$$

$$0 \le g \le \bar{g}$$
$$0 \le n_{ij} \le \bar{n}_{ij}$$
$$n_{ij} \text{ integer}; f_{ij} \text{ and } \theta_j \text{ unbounded}$$
$$(i,j) \in \Omega$$

where v is the investment cost in US$ (objective function); n_{ij} is the number of circuits added in path i–j; θ_j is the voltage phase angle at bus j; f_{ij} is the power flow on path i–j; g_k is the generation on bus k.

The parameters are represented by: c_{ij} – cost of the circuit added in path i–j. γ_{ij} is the susceptance of the circuit added in path i–j; n_{ij}^{o} is the number of circuits in the initial topology in path i–j; $\bar{f}_{ij}$ represents the maximum power flow of a line on path i–j; $\bar{n}_{ij}$ is the upper limit for the number of circuits added on i–j; $\bar{g}$ is the vector with generator upper limit and d is the vector of loads. Finally, S represents the branch-node matrix and Ω is the set of all branches.

The first constraint (2) is the power balance constraint (or the equivalent Kirchhoff's current law). The second constraint (3) is the line power flow and is equivalent to Kirchhoff's voltage law. Eq. (3) introduces nonlinearity into the problem. If (3) is removed, the model becomes the transportation model [3]. Some of the classical constructive heuristic algorithms relax the investment variables (n_{ij}) from the original model and based on the relaxed solution they define the next line to add in.

2.2. Hybrid linear model

According to [5], an intermediate relaxed model can be used to obtain solutions to the DC model, which is nonlinear, by solving only linear programming problems (or LP problems). In [5], a fictitious network called "overload network" is used to identify the right-of-ways to be considered for system expansion. The nature of this model is similar to the transportation network laid upon to another one that must follow both Kirchhoff's laws. After a circuit is selected for insertion, it must comply both laws for the next step. Therefore, there are two steps, one for circuit selection, based only on the transportation model and the second one that inserts the selected circuit to the model and forces it to follow both laws. With this strategy it is possible to obtain feasible solutions to the DC model by solving only linear programming (LP) problems [10]. Although the optimal solution will not result the same optimal solution of the DC model (1)–(4), its quality will be superior to the transportation model [3].

To illustrate the problem, suppose that in the first iteration of the constructive algorithm the following problem is solved.

$$Min v = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} \quad (5)$$

s.t.

$$Sf + S^0 f^0 + g = d \quad (6)$$

$$f_{ij}^0 - \gamma_{ij} n_{ij}^{o}(\theta_i - \theta_j) = 0 \forall (i,j) \in \Omega_0 \quad (7)$$

$$|f_{ij}^0| \le n_{ij}^{o} \bar{f}_{ij} \quad (8)$$

$$|f_{ij}| \le n_{ij} \bar{f}_{ij} \quad (9)$$

$$0 \le g \le \bar{g}$$

$$0 \le n_{ij} \le \bar{n}_{ij}$$