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Specialized differential evolution technique to solve the alternating current model based transmission expansion planning problem ☆

Santiago P. Torres *, Carlos A. Castro

University of Campinas (UNICAMP), Campinas, Brazil

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ABSTRACT

Solving the Transmission Expansion Planning (TEP) problem using the Alternating Current (AC) network model is a recent important trend. This problem is extremely difficult to solve due to its combinatorial nature and the non-linear behavior presented by using the AC network model, and only very few research works had tackled it so far. In this work, an improved and specialized application of Differential Evolution (DE) to solve the TEP problem in its static form, using the AC model and taking into account reactive power compensation is presented. The main goal of this work is to make feasible the use of the AC network model for TEP. This approach improves some features of traditional differential evolution in its binomial version to be applied to solve the TEP problem. Some comparisons are performed using some other swarm based meta-heuristics in order to demonstrate the good results obtained. Test and realistic networks are used to present the results of this new approach.

Introduction

Electric energy systems are facing major challenges in order to get a clean, sustainable and economically affordable electric energy supply. To achieve some of the above objectives, the Transmission Expansion Planning (TEP) problem plays a crucial role. The TEP problem consists of determining all the transmission infrastructure changes needed to meet the balance between demand and generation. In this problem, it is assumed that load and generation increases are known within a determined planning horizon. Traditionally, the use of the DC model has been current practice in TEP and literature about this topic is extensive [1–5]. However, in that case, the planner has to adjust or modify the plan in order to comply with the constraints imposed by the realistic non-linear behavior of active and reactive power flows. Therefore, there is enough evidence that the use of DC model may yield to wrong estimated investment costs, and the cost difference with plans obtained by taking into account AC power flows could be significant [1,6]. Therefore, the use of the AC model to solve the TEP problem is necessary in order to deal with this open issue.

Solving the TEP problem using the AC model is a very complex, combinatorial, non-convex, non-linear, mixed-integer problem. Therefore, there is no optimization technique that can assure that an optimal solution is obtained. For that reason, it is very appropriate and opportune to use meta-heuristic techniques that could offer good quality solutions in reasonable computing times to solve the problem. The AC model based TEP is not employed in utility practice yet presumably due to the following reasons: (i) the use of AC model in TEP is a relatively recent open issue (2007), (ii) there is a lack of solution methods to choose and (iii) there are no significant experiments that show that existing methods are robust enough. Very few research works have been published so far to deal with the AC model in TEP. Ref. [6] presented a Constructive Heuristic Algorithm (CHA) to solve the problem, where only dispatchable energy sources were taken into account. CHÁs algorithms do not provide good quality solutions for large and complicated systems; therefore, that approach is not practical for use in industry applications. More recently, reference [7] proposed a black box optimization model that dealt with limited control energy sources. That model generalizes the constructive heuristic optimization algorithms where only non-dispatchable generation is handled. The disadvantages of using this approach in utility practice are: (i) it only takes into account 100% of non-dispatchable energy sources without the possibility of including dispatchable generation, (ii) the black box approach is not easy to be implemented, and (iii) it is based in a CHA algorithm which often does not provide good quality solutions, as explained in [5]. Additionally, in [8], an AC formulation is proposed to take into account shunt compensation, however, the discrete nature of shunt

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* Corresponding author.
E-mail addresses: santiago.ieee@gmail.com (S.P. Torres), ccastro@ieee.org (C.A. Castro).

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compensation included in the formulation led to a combinatorial explosion, affecting the robustness of the approach and sometimes providing low quality solutions. A relaxed AC network model to solve the TEP problem, without the inclusion of reactive power compensation, is presented in [9]. In [10], the TEP problem using the AC model was solved by using Particle Swarm Optimization (PSO). In this research work, a DE approach to solve the TEP problem based on the AC formulation, with the inclusion of reactive power compensation, is proposed. DE has been used, in its traditional form, only in reference [11] to solve the TEP problem using the DC model only. The contributions included in this research work are: (i) a DE based approach using the AC network model including reactive power compensation, (ii) a better strategy to generate initial solutions which led to increased success rates, (iii) a better handling of the specialized function evaluation process in the selection part of DE which led the optimization process to employ a substantially smaller number of function evaluations (optimal power flows), and (iv) a comparative study among DE variations and some particle swarm based meta-heuristics. It is worth noting that this research work is aimed to demonstrate the feasibility of using the AC network model to solve the TEP problem; therefore, the TEP problem, in this research work, is considered static, and market and uncertainty issues are not taken into account, in the same way as done in Refs. [6–8].

The remaining of this paper is divided as follows. Section ‘Mathematical formulation’ presents the mathematical model used to solve the TEP problem. Section ‘Differential evolution’ explains the DE basics in order to provide an appropriate understanding of this work. Section ‘TEP implementation using DE’ shows the implementation issues using the DE proposed technique. In order to test this TEP application using the AC model, three test and realistic power networks are used, and the results are shown in Section ‘Results’. Section ‘Conclusion’ presents the conclusions and the possibilities of future research works.

Mathematical formulation

Mathematical modeling – AC model

The mathematical modeling used in this work is divided into two problems: (a) the expansion master problem, and (b) the operational problem.

The formulation of the transmission expansion master problem is as follows.

$$\min v = \sum_{(k,l)\in\Omega} c_{kl} n_{kl} + w, \tag{1}$$

subject to:

$$0 \le \boldsymbol{n} \le \bar{\boldsymbol{n}}; \boldsymbol{n} \text{ integer} \tag{2}$$

where v is the investment due to the addition of new circuits and the cost of load shedding and shunt compensation, c_{kl} corresponds to the cost of a circuit that can be added to the right of way between the buses $k - l$, n_{kl} is the number of circuits added to the right of way between the buses $k - l$, and w is the cost of active and reactive load shedding. Ω is the set of all rights of way; $\boldsymbol{n}$ is a vector with the total number of circuits (existing and added) in the current transmission topology, $\bar{\boldsymbol{n}}$ is a vector containing the maximum number of circuits allowed in any transmission topology.

The idea of (1) is to minimize the total cost of transmission line additions and the cost of load shedding. The load shedding cost is not only useful for quantifying this variable for the various expansion plans, but it is also important to penalize the objective function, in an easy way, in case the transmission topology is not operationally feasible. At each iteration of the expansion problem, a number of transmission topologies are generated by the meta-heuristic used in this paper namely the DE technique, to be explained in Section ‘Differential evolution’. Also, the operational feasibility of each generated transmission topology has to be evaluated. This is done through the independent optimization problem explained ahead in this section which provides the expansion problem with a measure of feasibility by means of the load shedding cost.

The operational problem provides the cost of the load shedding to the expansion problem, for each transmission topology. The operational problem corresponds to the formulation of an AC optimal power flow, with some operational constraints, as in the well-known DC model. In this case, the objective function includes the active and reactive load shedding, modeled by adding artificial generators to the PQ nodes in such a way that the load shedding is minimized. In this work, this is solved by a special interior point method implemented in MATPOWER [15]. Each evaluation of each transmission topology will be referred to as Function Evaluation (FE) in this paper. The complete formulation of the operational problem used in this paper is as follows.

$$\min w = \sum_{k\epsilon\Lambda} (\alpha_1 r_{pk} + \alpha_2 r_{Qk}) \tag{3}$$

Subject to

$$\boldsymbol{P}(\boldsymbol{V},\boldsymbol{\theta}) - \boldsymbol{P_G} + \boldsymbol{P_D} - \boldsymbol{r_P} = 0 \tag{4}$$

$$\boldsymbol{Q}(\boldsymbol{V},\boldsymbol{\theta}) - \boldsymbol{Q_G} + \boldsymbol{Q_D} - \boldsymbol{r_Q} = 0 \tag{5}$$

$$\underline{\boldsymbol{P}}_{\boldsymbol{G}} \le \boldsymbol{P_G} \le \bar{\boldsymbol{P}}_{\boldsymbol{G}} \tag{6}$$

$$\underline{\boldsymbol{Q}}_{\boldsymbol{G}} \le \boldsymbol{Q_G} \le \bar{\boldsymbol{Q}}_{\boldsymbol{G}} \tag{7}$$

$$\underline{\boldsymbol{r}}_{\boldsymbol{p}} \le \boldsymbol{r_p} \le \bar{\boldsymbol{r}}_{\boldsymbol{p}} \tag{8}$$

$$\underline{\boldsymbol{r}}_{\boldsymbol{Q}} \le \boldsymbol{r_Q} \le \bar{\boldsymbol{r}}_{\boldsymbol{Q}} \tag{9}$$

$$\underline{\boldsymbol{V}} \le \boldsymbol{V} \le \bar{\boldsymbol{V}} \tag{10}$$

$$\boldsymbol{S}^{from} \le \bar{\boldsymbol{S}} \tag{11}$$

$$\boldsymbol{S}^{to} \le \bar{\boldsymbol{S}} \tag{12}$$

where $\boldsymbol{r_P}$ is the active load shedding; α_2 is the cost of shunt compensation; $\boldsymbol{r_Q}$ is the reactive load shedding, which in this formulation also represents the reactive power compensation needed in some buses; the upper bound of variable $\boldsymbol{r_P}$ is the total load connected at the respective bus; $\boldsymbol{V}$ is the voltage magnitudes vector; α_1 the cost of the active load shedding; $\boldsymbol{\theta}$ is the phase angles vector; $\boldsymbol{P_G}$ and $\boldsymbol{Q_G}$ are the existing real and reactive power generation vectors; $\boldsymbol{P_D}$ and $\boldsymbol{Q_D}$ are the real and reactive power demand vectors; $\bar{\boldsymbol{P}}_{\boldsymbol{G}}, \bar{\boldsymbol{Q}}_{\boldsymbol{G}}$, and $\bar{\boldsymbol{V}}$ are the vectors of maximum real and reactive power generation limits and voltage magnitudes, respectively. In this work, the maximum and minimum voltage magnitude limits are set to 95% and 105% of the nominal value. $\boldsymbol{S}^{from}, \boldsymbol{S}^{to}$, and $\bar{\boldsymbol{S}}$ are the apparent power flow vectors (MVA) through the branches in both terminals and their limits, respectively. Λ is the set of all load buses. Eqs. (4) and (5) represent the conventional equations of AC power flow. $\boldsymbol{\theta}$ is unbounded.

The elements of vectors $\boldsymbol{P}(\boldsymbol{V},\boldsymbol{\theta})$ and $\boldsymbol{Q}(\boldsymbol{V},\boldsymbol{\theta})$ are calculated according (13) and (14), respectively.

$$P_k(\boldsymbol{V},\boldsymbol{\theta}) = V_k \sum_{k\epsilon\boldsymbol{M}} V_l [G_{kl} \cos\theta_{kl} + B_{kl} \sin\theta_{kl}] \tag{13}$$

$$Q_k(\boldsymbol{V},\boldsymbol{\theta}) = V_k \sum_{k\epsilon\boldsymbol{M}} V_l [G_{kl} \sin\theta_{kl} + B_{kl} \cos\theta_{kl}] \tag{14}$$

The components of $\boldsymbol{S}^{\boldsymbol{from}}$ and $\boldsymbol{S}^{\boldsymbol{to}}$ can be calculated according (15) and (16), respectively.