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Transmission network expansion planning considering repowering and reconfiguration

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ABSTRACT

Transmission expansion planning (TEP) is a classic problem in electric power systems. In current optimization models used to approach the TEP problem, new transmission lines and two-winding transformers are commonly used as the only candidate solutions. However, in practice, planners have resorted to non-conventional solutions such as network reconfiguration and/or repowering of existing network assets (lines or transformers). These types of non-conventional solutions are currently not included in the classic mathematical models of the TEP problem. This paper presents the modeling of necessary equations, using linear expressions, in order to include non-conventional candidate solutions in the disjunctive linear model of the TEP problem. The resulting model is a mixed integer linear programming problem, which guarantees convergence to the optimal solution by means of available classical optimization tools. The proposed model is implemented in the AMPL modeling language and is solved using CPLEX optimizer. The Garver test system, IEEE 24-busbar system, and a Colombian system are used to demonstrate that the utilization of non-conventional candidate solutions can reduce investment costs of the TEP problem.

Introduction

Transmission expansion planning (TEP) is a classic problem in electrical power systems; its goal is to find the optimal plan for expansion of lines and/or transformers to be installed in the network in order to allow a feasible operation in a pre-defined horizon at a minimum cost. The optimal expansion plan should define where, how many, and when new network elements (lines or transformers) must be installed. The necessary data for solving the TEP problem include: current topology, candidate circuits, generation, demand for year-horizon, and investment constraints, among others.

An ideal mathematical model for TEP should use the load flow equations from the Alternating Current (AC) Model. However, the use of these equations would result on a mixed-integer non-linear programming problem which optimal solution is not guaranteed by available classical optimization tools. Consequently, to solve the TEP in the long term, relaxed mathematical models are often used. These models generally use only the active part of the operation of a power system (active power and phase angle). Main models collected from the literature [1–3] are: (a) Transportation model Garver [4]; (b) Linear hybrid model Villasana et al. [5]; (c) Direct Current (DC) model; and (d) Linear Disjunctive Model Bahiense et al. [6].

The literature provides different approaches to the TEP problem that have been developed using the models above. Such approaches include, among others, multistage dynamic planning [7–9], demand uncertainty [10–12], and the inclusion of security constraints ($N-1$ criterion) [9,13–15]. Solutions for these mathematical models have been proposed in the literature using different optimization techniques such as metaheuristics [7,16–20], and mathematical programming, [4,6,15,21,22].

Despite of the great number of model adaptations and solution approaches applied to the TEP problem, there is not reference in

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Nomenclature

Constants

d_i	load in bus i
$\bar{g}_i$	maximum generation in bus i
c_{ij}	investment for the transmission in branch ij
$\bar{f}_{ij}$	maximum real power flow in branch ij
n^0_{ij}	number of existing transmission lines in the branch ij
$\bar{n}_{ij}$	maximum number of reinforcement that can be added in the branch ij
x^{pu}_{ij}	reactance of transmission branch ij
S_{base}	base power
$\bar{\theta}$	maximum phase angles in radians
$\bar{fr}_{ij}$	maximum real power flow in repowered branch ij
xr_{ij}	reactance of transmission repowered branch ij
crep_{ij}	investment for the upgrade of transmission in branch ij
c^r_{ij}	investment for the transmission in the repowered branch ij

Variables

$w_{ij,y}$	binary decision to add a new line in branch ij and circuit y
g_i	active power generation in bus i
θ_i	phase angle at bus i in radians
f^0_{ij}	real power flow in existing branch ij
$f_{ij,y}$	real power flow in added elements in branch ij and circuit y
$w_{a_k e_k,1}$	binary decision for reconfiguration between busbar a and e
$w_{b_k e_k,1}$	binary decision for reconfiguration between busbar b and e
$w_{a_k b_k,1}$	binary decision for reconfiguration between busbar a and b
r_{ij}	binary decision for repowering the existing branch ij
$w^r_{ij,y}$	binary decision of repowered added line in branch ij and circuit y
f^{0r}_{ij}	real power flow in repowered existing branch ij
$f^r_{ij,y}$	real power flow in repowered added elements in branch ij and circuit y

Sets

Ω_b	busbars set
Ω_l	branches set
Ω_k	set of candidate lines to be reconfigured

the specialized literature to the use of non-conventional solutions such as reconfiguration or repowering of existing network assets. In consequence, when using the classic modeling of the TEP problem there might be a gap between the proposed solution candidates and the real life solution that can be implemented. In this case real life solutions might include non-conventional candidates (i.e. network reconfiguration or repowering of existing network assets). Practice has shown that there are real life solutions including non-conventional candidates with a lower cost than proposed by classic models. Various examples of these solutions around the world include:

- Circuit reconfiguration Guavio – Tunal 230 kV in Guavio – Suria 230 kV and Suria – Tunal 230 kV in Colombia, [23].
- Circuit reconfiguration Guajira – Santa Marta 230 kV in Guajira – Termocol 230 kV and Termocol – Santa Marta 230 kV in Colombia, [23].
- New Grid Supply Point at Twinstead in UK including 132 kV network reconfiguration, [24].
- Repowering the existing circuit Trujillo Norte – Cajamarca Norte 220 kV, Tingo Maria – Vizcarra 220 kV, Vizcarra – Conococha 220 kV in Peru, [25].
- Repowering the circuit Itaipú-Margen Derecha 500 kV in Brazil, [26].
- Repowering the circuit Fortuna – Panama y 230 kV Guasquitas – Panama in Panama, [27].
- Midway-Temblor 115 kV Line Reconductor (repowering) by Pacific Gas and Electric Company in USA, [28].
- Reconductor (repowering) the Mickleton – Gloucester 230 kV parallel circuits with double bundle conductor by PJM in USA, [29].

Although in practice there might be other types of unconventional candidates (eg voltage level shift or three phase transformers), the reconfiguration and repowering of circuits are generally the most common unconventional candidates used in the TEP. As regards reconfiguration, network topology optimization has been explored in [30,31]. However, the main difference with the reconfiguration modeled in this paper is the fact that topology changes are proposed using existing and possible new circuits of the network.

The primary motivations for resorting to reconfiguration and repowering of circuits include the ever increasing environmental constraints and the difficulty in acquiring the easements and rights-of-way in major consumption centers (i.e. cities, industrial centers). Therefore, sometimes the only feasible solution for the TEP in major consumption centers are, in the mid-term, the use of FACTS [28], and in the mid and long term the reconfiguration or repowering of existing network.

In this paper the authors propose a model for TEP that includes non-conventional candidates. The main contributions of this paper are as follows:

(i) It provides a novel modeling for the TEP problem in which, besides new lines and two-winding transformers, the reconfiguration and repowering of existing network assets has also been considered.

(ii) The new constraints are added in such a way that the linear disjunctive model of the TEP problem remains a mixed-integer linear programming problem, which optimal solution can be obtained by commercially available software.

The rest of the document is organized as follows: Section 'A TEP model with commonly used candidates' describes the classic TEP model that considers commonly used candidate solutions. Section 'Introducing repowering and reconfiguration in the TEP problem' describes the modeling of non-conventional candidates of the TEP problem. Section 'Tests and results' provides the tests and results in different power systems. Finally, conclusions are presented in Section 'Conclusions'.

A TEP model with commonly used candidates

As it was already stated, there are different models for the TEP problem (AC, transportation, linear hybrid, DC and linear disjunctive). In particular, the disjunctive linear model [6] is a linear equivalent to the DC model. Because of this, the disjunctive linear