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An innovative disjunctive model for value-based bulk transmission expansion planning

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ABSTRACT

This paper presents an innovative modeling approach for multi-stage transmission network expansion planning (TNEP) optimization problem. It efficiently extends the traditional disjunctive model to allow multiple parallel circuit additions between two buses, by using a decimal-binary transformation mechanism. Case study results indicate that this method may significantly improve computational efficiency, particularly for multi-stage bulk transmission system planning optimization with high renewable penetration level, which usually considers building multiple parallel circuits for significant number of candidate route.

1. Introduction

The primary objective of traditional electric transmission network expansion planning (TNEP) optimization is to select transmission circuit additions with minimum investment cost to satisfy demand under future system scenarios. Previous studies have developed and well summarized the mathematical programming approaches [1,2]. Nonlinearities arising from use of the DC flow model, where bus voltage angles are multiplied by circuit investment decision binary variables, can be eliminated by applying the disjunctive mixed integer formulation [3–6].

The existing disjunctive model [3–6] requires all circuit investment decision variables to be binaries, allowing one circuit to be built on a single candidate route for the planning horizon. Bulk transmission expansion in a wide area may require building multiple parallel circuits on a certain candidate route [7,8], for reliability or economic purposes [9], particularly in multi-stage investment problems. An obvious solution is to model enough parallel candidates (one for each possible circuit addition). However, doing this greatly increases the model dimensions, especially when it is possible to add a large number of parallel circuits on one route, or when the upper limit on number of parallel circuits is difficult to estimate in advance. We encountered an extreme case of this situation when designing a high capacity interregional transmission overlay for the US under high renewable futures [10], which motivated the development reported here.

There is a growing interest in value-based planning which considers both transmission investment cost and generation production cost [11–13]. It considers the economic value of transmission, as well as reliability performance. Its execution can be greatly facilitated by computationally efficient TNEP optimization models. In this paper, we present a value-based TNEP model, called the "decimal-binary disjunctive model," which efficiently addresses the parallel circuit problem mentioned above. An associated algorithm is also presented to determine the optimal number of parallel candidates needed. Contributions of this paper mainly include:

1. Proposed an innovative disjunctive model for both single stage and multi-stage TNEP problems, which significantly improves modeling efficiency and computational effectiveness through a decimal-binary transformation and an inherent investment ordering. Both circuit investment cost and unit production cost are addressed in the objective function, making it a value-based transmission planning model with generation re-dispatch;
2. Developed an associated algorithm to determine optimal number of parallel candidate circuits which further improves

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Nomenclature

t	Time step
n	Number of nodes
m	Number of candidate circuits
b	Number of parallel candidate bundles needed for a certain m
H	Planning time horizon (set of time steps)
H_{inv}	Set of Investment time steps within H
$\Omega_i{}^0$	Set of existing circuits connected to bus i, $i = 1, n$
$\Omega_i{}^+$	Set of candidate circuits connected to bus i, $i = 1, n$
Ω_i	The union of $\Omega_i{}^0$ and $\Omega_i{}^+$
$f(t)$	Vector of flows on step t (existing and candidates)
$f0max(t)$	Vector of circuit capacities on step t (existing)
$fmax$	Vector of circuit capacities (candidates)
$g(t)$	Vector of bus generations on step t
$gmax(t)$	Vector of bus generation capacities on step t
$d(t)$	Vector of bus active loads
$\theta(t)$	Vector of bus voltage angles in radians on step t
$\theta ref(t)$	Reference bus voltage angles in radians on step t
$x(t)$	Investment decision binary vector on step t
$S(t)$	Cumulative investment decision vector on step t
cI	Vector of unit investment cost of candidates
co	Vector of unit generation production cost
$\gamma 0$	Vector of circuit susceptance (existing)
γ	Vector of circuit susceptance (candidates)
M	Vector of penalty factors of candidate circuits
$\beta(t)$	Discount factor for step t
$\Delta(t)$	Time duration for step t
D_R	Ratio of the circuit's flow capacity and its susceptance

modeling efficiency, and enables modeling of multiple types of transmission circuits including both HVAC and HVDC;

3. Provided a solution approach for solving large-scale real world planning problems beyond the regional level under high renewable penetration futures.

The remainder of this paper is organized as follows. Section III reviews the standard disjunctive model. Section IV introduces the new method. Section V describes three comparison case studies between the existing and new methods using IEEE 46-bus and 87-bus standard test cases, and high-dimension study case developed to study interconnection wide transmission design in real world. Section VI concludes.

2. The standard disjunctive model (Big-M approach)

In classical linearized DC flow model, a non-linear term appears due to the product of voltage angle and investment decision variables in the Kirchhoff's Voltage Law (KVL) constraints for candidate circuits. It can be eliminated by applying the disjunctive form of the KVL constraints, which transform one non-linear DC flow equation to two linear integer inequalities in (1-b) and (1-c). The existing multi-stage disjunctive model is formulated below, summarized from [1–6]:

$$Min\{x, f, g, \theta\} \sum_{t \in Hinv} \beta(t) cIx(t)$$

Subject to (1)

$$\sum_{k=(i,j) j \in \Omega i} fk(t) - gi(t) = di(t), i = 1, n \forall t \in H \quad \text{(a)}$$

$$fk(t) - \gamma k(\theta i(t) - \theta j(t)) = 0, \quad k = (i, j),\ j \in \Omega_i^0,\ i = 1, n \forall t \in H \quad \text{(b)}$$

$$-Mk(1 - Sk(t)) \le fk(t) - \gamma k(\theta i(t) - \theta j(t)) \le Mk(1 - Sk(t)),$$

$$k = (i, j), j \in \Omega_i^+, i = 1, n \forall t \in H \quad \text{(c)}$$

$$S(t) = \sum_{i \in Hinv, i \le t} x(i) \quad \text{(d)}$$

$$-f0_k^{max}(t) \le fk(t) \le f0_k^{max}(t), \quad k = (i, j), j \in \Omega_i^0, i = 1, n \forall t \in H \quad \text{(e)}$$

$$-f_k^{max} Sk(t) \le fk(t) \le f_k^{max} Sk(t), \quad k = (i, j), j \in \Omega_i^+, i = 1, n \forall t \in H \quad \text{(f)}$$

$$0 \le gi(t) \le g_i^{max}(t), i = 1, n \forall t \in H \quad \text{(g)}$$

$$\theta ref(t) = 0 \quad \text{(h)}$$

$$x(t), S(t) \in \{0, 1\}^m \quad \text{(i)}$$

Eq. (a) represents nodal power balance; (b) and (c) represent KVL for existing and candidate circuits respectively; (d) relates transmission investment on each investment time step t and cumulative investment until step t; (e) and (f) are transmission rating limits for existing and candidate circuits respectively; (g) is the generation output limits; (h) sets reference bus voltage angles to be 0, which could be eliminated by calculating bus angle differences only; (i) defines investment variables to be binary. Circuit resistances are neglected.

In (1-c), when there is investment on a candidate circuit, then:

$$Sk(t) = 1 \quad (2)$$

$$0 \le fk(t) - \gamma k(\theta i(t) - \theta j(t)) \le 0, \quad k = (i, j), j \in \Omega_i^+, i = 1, n \forall t \in H \quad (3)$$

When there is no investment on a candidate circuit, then:

$$Sk(t) = 0 \quad (4)$$

$$-Mk \le fk(t) - \gamma k(\theta i(t) - \theta j(t)) \le Mk, \quad k = (i, j), j \in \Omega_i^+, i = 1, n \forall t \in H \quad (5)$$

If M_k is large enough, (5) is equivalent to releasing the KVL constraints. The minimum value of M_k can be explicitly determined by the following approach ([14] and [15]):

If there is an existing circuit on the same route of candidate k, the minimum value of M_k is the product of existing circuit flow capacity and the ratio of candidate susceptance and existing circuit susceptance. The reason is that in Eq. (5), as $S_k(t) = 0$, according to Eqs. (1)–(f), $f_k(t)$ will also be zero. Then we have:

$$-Mk \le -\gamma k(\theta i(t) - \theta j(t)) \le Mk, \quad k = (i, j), j \in \Omega_i^+, i = 1, n \forall t \in H \quad (6)$$

no matter $\theta_i(t) \le \theta_j(t)$ or $\theta_i(t) \ge \theta_j(t)$, (6) is equivalent to:

$$\gamma k|\theta i(t) - \theta j(t)| \le Mk, \quad k = (i, j), j \in \Omega_i^+, i = 1, n \forall t \in H \quad (7)$$

The maximum possible angle difference happens when the flow on the circuit reaches its maximum capacity, i.e.:

$$|\theta i(t) - \theta j(t)| \max = f0_k^{max} \gamma k, \quad k = (i, j), j \in \Omega_i^0, i = 1, n \forall t \in H \quad (8)$$

From (7) and (8), the minimum value of M_k that keeps (5) non-binding would be:

$$Mk = f0_k^{max} \gamma k \gamma k \quad k = (i, j), j \in \Omega_i^0 \cap \Omega_i^+, i = 1, n \forall t \in H \quad (9)$$

If candidate k is in a new right-of-way, M_k is given by the product of the circuit's susceptance and the shortest distance between the circuit's terminal nodes which goes along existing circuits of other parts of the network. The distance, referred to as D_R below, is defined by [14] as the ratio of the circuit's flow capacity and its susceptance (in radians). It can be interpreted as the angular difference limit of a circuit. D_R is an important indicator which forms