Electric Power Systems Research 161 (2018) 1–7

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Approximate optimal transmission switching

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ARTICLE INFO

Article history:
Received 24 July 2017
Received in revised form 27 February 2018
Accepted 26 March 2018

Keywords:
Mixed integer programming
Power generation dispatch
Power system economics
Power transmission control
Approximate model
Transmission switching

ABSTRACT

Optimal transmission switching (OTS) has been proposed as a new control paradigm to improve the economics of electric power systems. The problem is formulated as mixed integer linear programming in which binary decision variables are used to represent the on and off state of transmission lines. In this paper, we propose an approximate model for the OTS problem to achieve better results in terms of solution quality and computation time. We prove the feasibility and optimality properties of our proposed approximate model through theorems. Through numerical studies we show that our proposed approximate model finds OTS solutions with the same electricity generation cost but with lower number of switched transmission lines in the same or less amount of time. Therefore, number of switched transmission lines is reduced to half, one-third, or even less, depending on the case study.

1. Introduction

The transmission line network is usually considered a static structure when determining the optimal economic dispatch of power generators. However, it has been pointed out in [1] that switching transmission lines into/out of service has multiple benefits. The hourly-based optimal transmission switching (TS) problem was first introduced in [2]. It is modeled as a mixed integer program (MIP) based on the traditional DC optimal power flow (DCOPF) problem. The objective of the optimization model is to minimize the energy generation cost for 1 h subject to supplying the load at that hour. The optimal TS problem was extended in [3] to include $N-1$ reliability requirements. Constraining the transmission switching to $N-1$ requirements ensures that the line on and off plan meets the NERC's single contingency reliability standard for power systems. On the other hand, constraining the transmission switching to $N-1$ requirements may lead to a conservative result [4], since the optimal solution should satisfy all the sets of contingency constraints at the same time. In [4] the corrective actions with respect to different contingencies is utilized to avoid conservative results when $N-1$ reliability requirements are applied. A transmission switching model that includes unit commitment and $N-1$ constraints has been proposed in [5]. All of these studies have reported noticeable savings in power generation costs when using transmission switching.

Different aspects of the optimal TS problem have been reported in the literature [6–12]. A just-in-time concept has been added to the optimal TS problem in [6] to improve the efficiency of a power system by removing inefficient lines from service and only using those lines in unusual situations. The effects of transmission switching on electricity markets were investigated in [7]. The study showed that transmission switching may result in considerable variability in nodal prices, generator payments, and load payments. The authors concluded that the transmission topology planning should be controlled and managed by unbiased and independent agencies with no interest in the financial outcomes of the switching decisions. In [8], the authors developed a disjunctive programming model to enhance the static security of transmission switching operations. Transmission switching has also been applied in capacity expansion planning [9,10], security constrained unit commitment [11,12], and optimal investment planning for dynamic transmission thermal rating [13]. In [14] transmission network switching is studied for reducing market power cost in generation sector where they develop a mathematical model that explores transmission switching from an economic perspective in the context of market power.

The formulated MIP for the hourly-based optimal TS is difficult to solve [2,5,15]. In [15] the authors show that the symmetry, the presence of more than one transmission line with the same impedance, thermal rating, and terminal buses, can adversely affect the computational requirement for solving the optimal TS problem. They introduce symmetry-breaking constraints and branching methods to deal with the symmetry in lines. To solve the optimal TS problem much faster, some heuristics have been proposed. A

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https://doi.org/10.1016/j.epsr.2018.03.021
0378-7796/

heuristic method has been reported in [16]. The method is based on a line-ranking parameter calculated using primal and dual solutions of the DCOPF problem. The line-ranking is used to detect lines that carry power flows from buses with high marginal cost to buses with low marginal cost. The detected lines are switched out of service. In [17] four transmission switching criteria are introduced to detect the switchable set of candidate lines. Another heuristic has been developed in [18]. The method uses two prescreening strategies to reduce the number of to-be-examined transmission lines for the optimal TS problem.

The economic transmission switching studies in [2,3,5–7] consider hourly TS for reducing costs. However, TS operation itself is a disruptive action and frequently switching lines into or out of service can create undesirable effects on the security and reliability of power systems [8]. In [19] an economic seasonal transmission switching (STS) model is developed where the economic TS operation occurs once at the beginning of a time period (e.g. season) and then the transmission topology remains unchanged during that period. The objective of STS model is to minimize the total generation cost over the season subject to loads and $N-1$ reliability requirements. It should be mentioned that periodic switching of transmission lines has been used for maintenance [20,21], and also for making trade-offs between protecting against potential contingencies in winter versus avoiding potential overloads in summer [1].

In this paper, we propose an approximate model for the optimal transmission switching problem. Our contributions in this paper are three folded. (1) Our proposed approximate optimal transmission switching (AOTS) is a new model in the literature. (2) We develop theorems that reveal interesting properties of our proposed approximate OTS model. (3) We show through numerical studies that our proposed approximate model finds OTS solutions with the same electricity generation cost but with lower number of switched transmission lines in the same or less amount of time.

This paper is organized as follows. Section 2 summarizes the notations used in this paper. Section 3 describes the original mathematical programming model for optimal transmissoin switching. Section 4 proposes an approximate mathematical model for optimal transmission switching problem where the proposed approximate model is studied and its properties are proved through theorems. Section 5 is the numerical experiments where the proposed model and the original model are demonstrated on test power systems. Section 6 gives the conclusions.

2. Notations

Indices

k	transmission line
n	generator
b	bus
a_k	origin bus for line
kb_k	destination bus for line k

Sets

Φ_b^-	set of lines consuming power from bus b
Φ_b^+	set of lines injecting power to bus b
η_b	set of generators at bus b

Parameters

K	number of transmission lines
N	number of generators
B	number of buses
C_n	operational cost of generator n
D_b	electricity load at bus b
$F_k^{\max}$	rating of transmission line k
Y_k	electrical susceptance of transmission line k
$G_n^{\min}$, , $G_n^{\max}$	min and max generation for generator n
$\Theta_k^{\max}$	max phase angle difference between origin and destination buses for line k
$Z^{\max}$	max number of lines that can be out of service

Variables

z_k	switching state of line k (0 out of service, 1 in service)
g_n	power generated by generator n
θ_b	phase angle at bus b
f_k	real power flow transmitted by line k

3. OTS model

The OTS model is an extension of the DCOPF model where the transmission topology is assumed switchable. We use the OTS model given in [2] and described by Eqs. (1a)–(1f).

$$\text{Min, } P_1 = \sum_n C_n g_n \tag{1a}$$

Subject to

$$\sum_{n\in\eta_b} g_n + \sum_{k\in\Phi_b^+} f_k - \sum_{k\in\Phi_b^-} f_k = D_b \quad \forall b \tag{1b}$$

$$-(1-z_k)M_k \le f_k - Y_k(\theta_{a_k} - \theta_{b_k}) \le (1-z_k)M_k \quad \forall k \tag{1c}$$

$$-F_k^{\max} z_k \le f_k \le F_k^{\max} z_k \quad \forall k \tag{1d}$$

$$G_n^{\min} \le g_n \le G_n^{\max} \quad \forall n \tag{1e}$$

$$-\Theta_k^{\max} \le \theta_{a_k} - \theta_{b_k} \le \Theta_k^{\max} \quad \forall k \tag{1f}$$

The mixed integer program (1) is difficult to solve especially when the number of transmission lines is large. In [2] constraint (2), in the following, is proposed to alleviate the computational difficulty of problem (1).

$$\sum_k (1-z_k) = Z^{\max} \tag{2}$$

The objective function (1a) minimizes total electricity generation costs. Constraints (1b) ensure that the power flowing into each bus equals the power flowing out of each bus. The physical relation between voltage angles of connected buses and the power flow in connecting lines is represented by constraints (1c). Thermal limits of lines are respected by constraints (1d) and generation capacities of generators are assured by constraints (1e). The bounds on the phase angle differences of connected buses are enforced by constraints (1f). The state of binary variable z_k denotes that line k is in service ($z_k = 1$) or out of service ($z_k = 0$). The left and right hand sides of constraints (1d) are multiplied by binary variables z_k to ensure there is no power flow in lines that are out of service. If a line is in service ($z_k = 1$), then inequality (1c) will be equivalent to the equality $f_k = Y_k(\theta_{a_k} - \theta_{b_k})$. On the other hand, if a line is not in service ($z_k = 0$), then inequality ((1c)) will be independent of power flow variable f_k but will include the disjunctive parameter M_k. By setting the value of this parameter to a sufficiently large number, the inequality constraints (1c) will be redundant when the corresponding line is switched out of service. However, a lower value for this parameter results in a stronger linear programing relaxation and is, therefore, desirable.

Tuning the disjunctive parameter for the transmission expansion problem is discussed in [22]. In their method, a shortest or longest path problem is solved for every line to find the minimum value (M_k^*) for the disjunctive parameter. This method can