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Energy and reserve scheduling with post-contingency transmission switching

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ABSTRACT

For security reasons, transmission systems are designed with redundancies. Prior works have identified the benefits to system operations when the transmission assets have a pre-contingency schedule. The system operator chooses the optimal network topology regarding the contingencies, but the transmission system is not capable of performing corrective actions. This paper highlights the economic and security benefits of an enhanced system operation with the advent of a smart grid technology by introducing a novel model. The proposed model is a joint energy and reserve scheduling one that incorporates the network capability to switch transmission lines as a corrective action to enhance the system capability to circumvent contingency events. The main goal is to reduce operating costs and electric power outages by adjusting the network connectivity when a contingency occurs. In such a framework, results show that with a limited number of corrective switches, the system operator is able to circumvent a wider range of contingencies while resulting in lower operational costs and reserve levels.

1. Introduction

Traditionally, system operators (SOs) treat transmission assets as fixed resources in scheduling models [1,4]. Notwithstanding the traditional approach, specific changes in the grid topology can be performed in real time to improve the system reliability [5,6]. These changes follow some previously agreed rules (see [7,8]) or, in certain cases, are based on the SOs experience. Therefore, current operation standards do not consider the grid topology as a decision in day-ahead scheduling models.

As customary in network-constrained generation scheduling models, a linearized DC power-flow approximation is used in this work to represent network capacity constraints while keeping the model tractable when considering unit commitment decisions [9,10]. At first glance, switching off a transmission line in a DC network may be seen as paradox [11]. If a line is available with zero cost, it is reasonable to use it during the system operation. In a tree-network topology, this statement is true. The only rule that matters is Kirchhoff's current law. Nevertheless, if the network has cycles, then Kirchhoff's voltage law must be met as well. Each cycle in the network adds one constraint in the optimization model. To improve the system operation, switching off a line can be beneficial to avoid the cycle constraint. Therefore, in a meshed network, taking out a line is a tradeoff between Kirchhoff's voltage and current laws.

Recent research has shown that considering the grid topology as a decision variable improves the system security while reducing operating costs: [10,12–14]. Fisher et al. [12] developed a transmission switching (TS) and generation dispatch model, by means of a mixed-integer-linear program (MILP), to supply the demand during a single period of time. These authors found a cost reduction of 25 percent for the standard 118-bus IEEE. Hedman et al. [13] analyzed the impact of $n-1$ security criteria in a previous work [12] and found a 15 percent saving for the 118-bus IEEE test system. They also applied this methodology to the 73-bus IEEE tests system and found a cost reduction of eight percent. It is worth mentioning that no cost reduction was verified for the 73-bus system in the absence of a security criterion. Lastly, Hedman et al. [10] considered the unit commitment problem with transmission switching on the day-ahead scheduling. They showed that an optimal network topology exists for each hour of the planning horizon. Hedman et al. [14] proposed the concept of just-in-time transmission, which motivates the use of TS as a corrective action. In [14], the model discussed in [12] is used to accomplish TS and two heuristic approaches were used to tackle the problem.

In [10], the TS benefit is considered as a preventive action in a unit commitment model. The SO determines the optimal pre-contingency scheduling for the generation and transmission assets,

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Nomenclature

Constants

C	total number of contingencies
c_i^V	variable cost coefficient offered by generator i
c_i^F	the fixed cost coefficient offered by generator i
c_i^{RD}	cost rate of generator i to provide down-spinning reserve
c_i^{RU}	cost rate of generator i to provide up-spinning reserve
d_n	real power load at bus n
I	number of generators
K	number of transmission lines
L	number of switchable lines
M_l	big M parameter by line l
P_{base}	constant used to transform per-unit into real power units
$P_i^{\max}$	maximum real power output of generator i
$P_i^{\min}$	minimum real power output of generator i
$F_l^{\max}$	maximum power flow of transmission line l
$F_l^{\min}$	minimum power flow of transmission line l
$\bar{R}_i^U$	upper bound for the up-spinning reserve of generator i
$\bar{R}_i^D$	lower bound for the down-spinning reserve of generator i
x_l	reactance of line l
$\lvert\mathcal{L}^{TS}\rvert$	number of switchable lines
$\Delta z^{\max}$	maximum number of lines that are switched different of the pre-contingency lines' states
Γ_{ic}	contingency indicator of generator i, which values 1 if generator i is out in the post-contingency state c, being 0 otherwise
Γ_{lc}	contingency indicator of line l, which values 1 if line l is out in the post-contingency state c, being 0 otherwise
Φ	number of fundamental cycles in the network
$\theta_n^{\max}$	maximum phase angle at bus n
$\theta_n^{\min}$	minimum Phase angle at bus n

Variables

$f_{l,c}$	power flow of line l in the post-contingency state c
$f_{l,0}$	power flow of line l in the pre-contingency state
$p_{i,c}$	real power output of generator i in the post-contingency state c
$p_{i,0}$	real power output of generator i in the pre-contingency state
r_i^D	down-spinning reserve of generator i
r_i^U	up-spinning reserve of generator i
u_i	binary variable that is equal to 1 if generator i is on and is 0 otherwise
$z_{l,c}$	transmission switching variable of line l, which is 1 if line l is connected and is 0 if it is open
$\delta_{n,c}$	load shedding in bus n under post-contingency state c
$\Delta z_{l,c}$	corrective action variable of line l in the post-contingency state c, which values 0 if $z_{l,c} = z_{l,0}$ and 1 otherwise
$\theta_{n,c}$	phase angle at bus n in the post-contingency state c

Functions

$C_i^P(.)$	production-cost function offered by generator i

Sets

$\mathcal{C}$	set of contingency states (including the pre-contingency state $c = 0$)
$\mathcal{F}_n$	set of lines with origin at bus n
$fr(l)$	origin bus of line l
I_n	set of generators connected to bus n
N	set of buses
$to(l)$	destination bus of line l
$\mathcal{T}_n$	set of lines with destination at bus n
$\mathcal{L}$	set of transmission lines
$\mathcal{L}^{TS}$	set of switchable transmission lines

Indexes

c	index of contingency states
i	index of generators
l	index of transmission lines
n	index of buses

but only generators are considered to respond against the loss of system components in post-contingency states. Moreover, a cost-based reserve allocation was not considered in such work, despite its intrinsic dependence on the network topology and the increasing appeal for optimization procedures to schedule optimal reserve levels in a joint energy and reserve market (see [1–3,15]). As a result, the least cost reserve deliverability was not accounted for in any of the previous TS-related works. Moreover, TS is not considered as a corrective action in any of the previously reported modeling approaches.

Therefore, the main objective of this work is to propose a novel joint energy and reserve scheduling model that accounts for TS in both pre and post-contingency states. This can be seen as an application of a smart network in which the system operator incorporates economic and security benefits of fast TS actions into the schedule. To accomplish the objective of this work, the model in [2] is extended to consider TS actions by means of binary variables for the pre and post-contingency states. Therefore, the proposed model co-optimizes the joint generation schedule, of energy and reserves, and the transmission topology. The goals of the proposed model are twofold: (i) to reduce electrical power outages by adjusting the network connectivity when a contingency occurs and (ii) ensure the deliverability of reserves through the network at the least cost.

The main contributions of this work are the following:

1. the development of a new MILP-based joint energy and reserve scheduling model that accounts for TS actions not only on the pre-contingency state, as done in [10,12,13], but also as a corrective action in all post-contingency states.
2. to show the proposed model is capable of enhancing power system reliability while reducing reserve levels and dispatch costs.

The rest of this work is organized as follows. In Sections 2 and 2.1 introduces the concept of preventive and corrective actions in TS, subsection 2.2 introduces the tradeoff between Kirchhoff's current and voltage laws, Section 2.3 provides a illustrative example to motivate the use of a joint energy and reserve scheduling model to capture the benefits of corrective TS actions, and Section 2.4 presents the relationship between the number of buses and lines in the system and an upper bound for the number of optimal switches. After that, Section 3 describes the proposed model, Section 4 shows the computational results of the application of the proposed model for two power systems, and lastly, Sections 5 and 6 present the main conclusions of this work and future research topics, respectively.