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Security-constrained transmission switching with voltage constraints

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ABSTRACT

Transmission switching (TS) would play a vital role in the security and economics of electric power systems. The application of TS to the AC model of security-constrained unit commitment (SCUC) for the day-ahead scheduling is presented in this paper. The proposed AC model of SCUC with TS would include real and reactive power flow constraints which increase the controllability of base case and contingency solutions with voltage constraints. A general FACTS model is introduced for the reactive power management in SCUC which is based on the power injection model (PIM). A modified Newton–Raphson power flow model is introduced in the proposed SCUC with TS in which line flows are considered as variables. The proposed AC network model is compared with the DC network model for enhancing the power network controllability and minimizing the operation cost. The case studies exhibit the effectiveness of the TS application to SCUC with AC network constraints.

1. Introduction

Recent market design proposals consider a more active role for transmission owners. Incentives are provided for transmission owners to increase investments in transmission and to utilize transmission lines more efficiently. Considering that building new transmission lines to meet the growing demand is a difficult and time-consuming task, the more efficient use of the existing transmission network would be a valuable alternative. Transmission switching (TS) is an efficient approach to utilize the power grid more comprehensively. TS will take specific transmission lines temporarily out of service in order to benefit from the modified network topology. This capability will be considered primarily for the newly installed transmission lines in the electricity market. TS has gained further attention since the FERC order 890 has called for an economic utilization of transmission capacity and hence made TS more favorable for economic purposes. The independent system operator (ISO) may apply TS as a corrective action for mitigating transmission flow violations [1–4], as a congestion management tool [5], for enhancing the power system security [6–9], and improving the system economics while maintain the security constraints [10]. TS would manage topology changes which could affect nodal prices, load payments, generation revenues, congestion costs, and flowgate prices. It can also improve the solution of the capacity expansion planning problem while providing economic benefits [11,12].

Much of the previous studies considered the TS for real power flow adjustments. In this paper, the optimal TS is considered for mitigating both transmission flow and bus voltage violations in the security-constrained unit commitment (SCUC) problem. To consider voltage constraints, a modified Newton–Raphson model is utilized which will satisfy the base case and contingency constraints. The proposed SCUC solution uses the Benders decomposition to decompose the model into a master problem and two subproblems [13–17]. A general model of FACTS devices is incorporated in the proposed SCUC formulations, which is capable of modeling all types of series, shunt or shunt-series FACTS devices. These features will add a comprehensive perspective to the SCUC formulation for TS applications.

Fig. 1 depicts the flowchart of the proposed SCUC model with AC network constraints. Benders decomposition is utilized to decompose the SCUC problem into smaller and easier to solve subproblems. The master problem uses the available market information to find the optimal hourly schedule of units (UC) by considering the prevailing UC constraints [18–20]. The hourly solution of UC is used in the subproblems to examine the AC network constraints. The TS ability of lines is considered and FACTS devices are incorporated in the subproblems if violations are detected. TS binary variables are determined via UC and consequently, they are considered as constant values in the subproblems. Given the unit and line schedule by the UC solution, the Subproblem 1 will check the base case network feasibility. In this subproblem, slack variables for real and reactive power mismatches are minimized based on line flow and FACTS device adjustments. The proposed Benders cut incorporates slack variables for the real and reactive power mismatch that is mitigated by recalculating the unit and line schedules. A converged base case power flow will be achieved based on the UC results. The Contingencies Network Check subproblem, i.e., Subproblem 2, uses the UC solution for the base case

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Nomenclature

Indices

b, m, n	indices for bus
c	index for contingency
i	index for generator
l	index for line
ns	index for non-switchable line
s	index for switchable line
Sh	superscript for shunt power injections
Se	superscript for series power injections
t	index for time

Sets

B_b	set of FACTS devices connected to bus b
L_b	set of lines connected to bus b
U_b	set of units connected to bus b

Parameters

M	large positive constant
NB	number of buses
NG	number of units
NNS	number of non-switchable lines
NS	number of switchable lines
NT	number of time periods
$PL_l^{\max}$	real power flow limit of line l
$Q_i^{\min}, Q_i^{\max}$	reactive power generation limits of unit i
UX_{it}	contingency state of unit i at time t
UY_{lt}	contingency state of line l at time t
$V_b^{\min}, V_b^{\max}$	voltage magnitude limits of bus b
α_b	power injection coefficient of FACTS device
δ_i^{max}	standing phase angle difference limit of line l
Λ_i	permissible real power adjustment of unit i

Variables

I_{it}	commitment state of unit i at time t
$MP_{bt,1}, MP_{bt,2}$	slack variables for real power mismatch in bus b at time t
$MQ_{bt,1}, MQ_{bt,2}$	slack variables for reactive power mismatch in bus b at time
P_{it}	real power generation of unit i at time t
PF_{bt}	real power injection in bus b at time t due to FACTS device
PL_{lt}	real power flow of line l at time t
Q_{it}	reactive power generation of unit i at time t
QF_{bt}	reactive power injection in bus b at time t due to FACTS device
QL_{lt}	reactive power flow of line l at time t
V_{bt}	voltage magnitude of bus b at time t
w_t	total mismatch at time t
z_{lt}	switching state of line l at time t
θ_{bt}	voltage angle of bus b at time t
$\psi_{it}, \mu_{lt}, \pi_{it}$	dual variables

Symbols

$\wedge$	given variables

Matrices and vectors

$\mathbf{1}$	vector of ones
$\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$	Jacobian matrices
$\mathbf{dP_0}$	real power mismatch vector
$\mathbf{dQ_0}$	reactive power mismatch vector
$\mathbf{MP_1}, \mathbf{MP_2}$	vector of slack variables for real power mismatch
$\mathbf{MQ_1}, \mathbf{MQ_2}$	vector of slack variables for reactive power mismatch
$\mathbf{X}$	bus-line incidence matrix
$\mathbf{Y}$	bus-unit incidence matrix
$\mathbf{\Delta P}$	real power generation increment vector
$\mathbf{\Delta PL}$	real power flow increment vector
$\mathbf{\Delta PL^{min}}, \mathbf{\Delta PL^{max}}$	real power flow lower and upper increment vectors
$\mathbf{\Delta Q}$	reactive power generation increment vector
$\mathbf{\Delta Q^{min}}, \mathbf{\Delta Q^{max}}$	reactive power generation lower and upper increment vectors
$\mathbf{\Delta QL}$	reactive power flow increment vector
$\mathbf{\Delta V}$	bus voltage increment vector
$\mathbf{\Delta V^{min}}, \mathbf{\Delta V^{max}}$	bus voltage lower and upper increment vectors
$\mathbf{\Delta \theta}$	bus phase angle increment vector
$\mathbf{\Delta \Lambda^{min}}, \mathbf{\Delta \Lambda^{max}}$	real power generation adjustment lower and upper increment vectors

to check the system security in case of contingencies. Using AC power flow equations, both real and reactive power mismatches are minimized in this subproblem. It is required to limit the standing phase angle difference to safeguard the rotor shaft. Different approaches are proposed to obtain the minimum generation redispatch in a reasonable time for desired standing phase angles [21–26]. This problem which is inevitable in restoration practices may also occur in the normal operation of power systems when attempting to reclose a single line that is a part of a transmission loop [23]. To present a practical TS model, the standing phase angle difference limit of switchable lines is formulated in our proposed model.

FACTS devices are incorporated here in the SCUC model. FACTS devices are traditionally modeled by a voltage (current) source model (VSM). VSM formulates the device according to the operating conditions, thus representing the device intuitively. However, it destroys the symmetric characteristics of the admittance matrix and may cause oscillations in the power flow solution in successive iterations. A more common approach, as used in this paper, is to utilize power injection model (PIM). The PIM is derived from VSM, in which real and reactive power injections are considered as independent control variables, as shown in Fig. 2. Using PIM, the symmetric characteristics of admittance matrix is kept and the oscillations in the power flow solution are mitigated. Due to advantages of the PIM, this model were extended to almost all FACTS devices and used in most of the researches on operation and control of power systems with FACTS devices. Table 1 represents the required PIM components for modeling different FACTS devices. The power injections are only interim results, where they would be converted to the corresponding VSM parameters once the solution is obtained. The control parameters and the required conversion to obtain control parameters from PIM components are not listed in the table since it can be found in the literature.

The rest of the paper is organized as follows. Section 2 presents the formulation of the problem. Section 3 conducts the numerical simulations and in detail discusses results obtained for the IEEE 118-bus system. Finally, concluding remarks are drawn in Section 4.

2. Security-constrained reactive power formulation

The step by step procedure for the solution of the proposed SCUC model is given as follows.

2.1. UC (optimal hourly schedule of units)

The UC solution provides the hourly generation dispatch and the state of switchable lines in both base case and contingencies.