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Generation and transmission equipment maintenance scheduling by transmission switching and phase shifting transformer

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Abstract
This paper models and investigates the incorporation of economic transmission switching (TS) into generation and transmission equipment maintenance scheduling (GTEMS) with the presence of phase shifting transformers. Adding TS and phase shifting transformer to the traditionally static transmission system makes it more flexible. The N-1 secure GTEMS with TS problem is formulated as a mixed-integer linear programming model. This problem is hard to solve by off-the-shelf commercial optimization solvers because on the one hand maintenance scheduling variables couple several time intervals together and on the other hand TS variables link normal and contingency states. A solution approach is proposed in this paper to address the problem's high computational burden, which decomposes the problem into a GTEMS subproblem and an optimal TS subproblem and solves them iteratively. The proposed model and decomposition approach are implemented on IEEE 30-bus test system. The results demonstrate that considering TS in GTEMS alters the maintenance schedule and brings cost saving.

KEYWORDS
decomposition approach, generation and transmission equipment maintenance scheduling, generation maintenance scheduling, transmission maintenance scheduling, transmission switching

1 | INTRODUCTION

The emergence of smart transmission networks provides several opportunities to improve and optimize electricity transmission systems.[1] Transmission lines are generally treated as static assets which their statuses do not change except for maintenance and contingency situations. Recently, the economic transmission switching (TS) and phase shifting transformer as FACTS devices have been considered as an opportunity for the flexibility of the transmission system. Although TS can be used as a corrective action in contingencies to address undervoltage and overvoltage situations as well as transmission overloading, economic TS aims to control the transmission topology in the normal situation to attain lower operation cost. Also, phase shifting transformer (PST) can be used to control transmission flow by changing the phase angle of its associated transmission line. Even though TS is an operational action, it may affect on medium-term and long-term power system decisions.[2-4]

In reviewer paper, TS as a corrective action is used to achieve different goals. In Wei and Vittal,[5] line and bus-bar switching as corrective actions are used to alleviate overload of lines and undervoltage or overvoltage violations happened by contingencies. Corrective TS as a congestion management tool can be used by the system operator to relieve overloads instead of dispatching costly generators or load curtailment. Corrective TS is used in Schnyder and Glavitsch[6,7] to improve system security and to minimize loss and/or cost reduction respectively. In Fisher et al,[8] economic TS is incorporated into optimal power flow problem. The objective function of the resulting mixed-integer linear program (MILP) problem is minimizing dispatch cost, and no security criterion is considered in the model. The model of Fisher et al[8] is used in Hedman et al[9] to study the impacts of TS on prices and players, eg, generators and loads, in the market environment as well as the computational aspects. In Hedman et al,[10] the N-1 security constraints are added to the model presented in Fisher et al.[8] A 2-stage robust optimal power flow with TS considering N-K contingency constraint security criterion is proposed in Ding and Zhao.[11] In Yu-Chi et al,[12] transmission constraints are accounted for in short-term optimal operation of power systems. The model of Hedman et al,[10] which is defined for only 1 time interval, is extended in Hedman et al[13] to account for intertemporal generator constraints such as maximum ramp up and ramp down rates as well as minimum down and up times which results in a security-constrained unit commitment (SCUC) with TS problem. The problem is solved by decomposing it into a SCUC subproblem and a security-constrained TS subproblem. The results show that the unit commitment schedule may be changed by changing the transmission topology. The SCUC with TS problem is formulated and solved in Khodaei and Shahidehpour[14] by decomposing the problem into SCUC master problem and TS subproblem. Generation and transmission expansion planning with TS problem is formulated and solved in Khodaei et al.[2] Transmission expansion planning with TS problem is formulated as MILP models considering element failure and demand uncertainty in Zhang et al[3] and Schumacher[4] respectively. The results exhibit that TS may alter the expansion plan. To calculate locational marginal prices and study the impacts of the optimal TS on the electricity node prices, the dual problem of the MILP model presented in Hedman et al[10] is formed by fixing the binary variables to their optimal values. A heuristic greedy algorithm is proposed in Balasubramanian and Hedman[15] to address the high computational burden of corrective TS for real-time applications. Robust optimization and chance constrained programming methods are used to cope with load and wind power uncertainties in optimal TS problems in Korad and Hedman[16] and Feng and Jianhui[17] respectively. A real-time contingency analysis tool with corrective TS is proposed in Balasubramanian et al,[18] and its comparison with the Pennsylvania-New Jersey-Maryland list of corrective switching solutions shows that this paper's proposed tool provides significant saving. Information gap decision theory is used to deal with wind generation uncertainty in SCUC with TS problem in Nikoobakht et al.[19] Economic TS for power systems with limited automation and control systems is considered in Jabarnejad[20] which leads to a seasonal economic TS problem wherein switching only happens at the beginning of each time interval (season). In Zhu et al,[21,22] new multiobjective optimization model is introduced for generation and transmission equipment maintenance scheduling (GTEMS), in which load is transferred for avoiding adverse problem in maintenance scheduling such as high load shedding during heavy loading conditions. Optimal phase angel injection model is used to model the impact of FACTS devices in Joseph et al.[23]

In Silva et al,[24] transmission constraints are incorporated into generation maintenance scheduling (GMS) problem. In view of tight GMS constraints in current power systems, a fuzzy MILP formulation is proposed in Leou[25] to seek for the solution with minimum violations from the desired plan. An incentive-based coordination mechanism for GMS between the system operator and generation companies (Gencos) in a restructured power system is proposed in Conejo et al,[26] in which the Gencos maximize their profit over the scheduling horizon whereas the system operator makes sure a predetermined level of reliability. In Barot and Bhattacharya,[27] an iterative coordination approach similar to Conejo et al[26] based on unserved energy is proposed for GMS in deregulated power systems. Generation maintenance scheduling in electricity markets is modeled as a noncooperative dynamic game which is performed by ISO in Min et al.[28] In Pandzic et al,[29] GMS is modeled as a mathematical programming with equilibrium constraints for each Genco, and then, all of these GMS problems are joined together which forms an equilibrium problem with equilibrium constraint. A modified Benders' decomposition in Changlin et al[30] solved short-term transmission maintenance scheduling (TMS). Generation maintenance scheduling considering long-term SCUC problem is solved by Benders' decomposition and relaxation induced algorithms in Wang et al.[31] A similar approach is used to solve GMS in electricity markets in Wang et al.[32] A risk-based approach for TMS is presented in Yong et al.[33] A bilevel TMS model, in which the upper level program aims at maximizing the transmission capacity margin whereas the lower level program mimics the market clearing for all time intervals in the TMS planning horizon, is proposed in Pandzic et al.[34] Generation maintenance scheduling and TMS affect on each other that in Ahmad et al[35] consider both together. It is beneficial to consider both of these problems together which is called integrated maintenance scheduling (IMS). In Marwali,[36] IMS problem is decomposed into a master problem in which the maintenance decisions are taken and subproblems which aim at minimizing the operation cost. An IMS model considering N-1 contingencies is proposed in Feng.[17] Stochastic coordination of IMS and SCUC is studied in Wang[37] in which Lagrangian relaxation method is used to separate and solve the problem. Integrated maintenance scheduling is formulated as a biobjective optimization problem with the aim of minimizing cost and maximizing reliability in Subramanian et al.[38] A model for GMS is proposed in Suresh and Kumarappan[39] which aims to reduce loss of load probability as a power system reliability measure. Modified versions of teaching learning algorithm, genetic algorithm, and particle swarm optimization are used to solve to maintenance scheduling problems in Subramanian et al,[38] Suresh and Kumarappan,[39] and Kim and Geem[40] respectively.

Although in traditional power system, transmission asset considered static, this paper presents a model for combination of transmission switching with the generation and transmission equipment maintenance scheduling in a more flexible transmission system which the phase shifting is considered. Both PST as 1 of the FACTS devices and TS, increase the system flexibility with releasing capacity of transmission line and changing power flow of transmission line. Transmission switching and PST are released more capacity of the transmission lines for efficient use of the power system by changing the network topology and the bus phase.

This paper provides a model for incorporating TS into the GTEMS problem and a decomposition approach for solving it. According to the presented literature review, economic TS is taken into account in short-term scheduling (eg,[9,10,13,14,21,22]) as well as long-term expansion planning (eg,[2-4]) models, all of which show that incorporating TS into the planning problems may result in lower system cost as well as modified operation and expansion plans. However, to the best knowledge of the authors, it is the first time that a decomposition approach is proposed to solve the problem of GTEMS incorporating TS and PST.

The preventive maintenance of power system components is used to decrease the forced outages of them. However, planned outages of generation units and transmission lines decrease the available generation and transmission capacity which may reduce the security of supply. In addition, disconnecting transmission lines could degrade security. Therefore, the power system security should be accounted for systematically in GTEMS with TS (GTEMSTS) problem to address these concerns. In this paper, N-1 contingency constraints are included in the proposed model to take contingencies into account.

The GTEMS problem comprises several snapshots which mimic the power system operation. Moreover, these snapshots are linked by the component outage decision variables. In addition, maintenance and TS decision variables link the normal and contingency states together. Therefore, GTEMSTS is a large-scale mixed-integer optimization problem with high computational burden which may not be solved by commercial solvers in a reasonable time. In this paper, the decomposition approach of Hedman et al[13] is adapted to address the high computational burden of GTEMSTS problem, in which the problem is decomposed into a GTEMS subproblem and an economic TS one.

The paper is organized as follows: After Section 1, the formulation of the GTEMSTS problem is presented in Section 2. The decomposition strategy is provided in Section 3. The numerical results of implementing the proposed model and decomposition strategy are discussed in Section 4. The concluding remarks and future works are presented in Section 5.

2 | PROBLEM FORMULATION

The objective function of the problem defined in (1) is minimizing the system cost over the planning horizon composed of generation and transmission maintenance costs as well as the fuel cost.

$$\min_{\boldsymbol{\Omega}} \begin{pmatrix} \sum_{\forall g \in G_m, \forall t} H_{gt} \cdot X_{gt} + \sum_{\forall l \in L_m, \forall t} H_{lt} \cdot Y_{lt} + \\ \sum_{\forall g, \forall t} c_g \cdot DT_t \cdot P_{gt}^n \end{pmatrix} \tag{1}$$

where $\boldsymbol{\Omega} = \{X_{gt}, \forall g \in G_m, \forall t, Y_{lt}, \forall\, l \in L_m, \forall\, t, Z_{lt}, \forall\, l \in L_s, \forall\, t, P_{gt}^c, \forall g, \forall t, \forall c, F_{lt}^c, \forall l, \forall t, \forall c, \theta_{bt}^c, \forall b, \forall t, \forall c, \delta_{bt}^c, \forall b, \forall t, \forall c\}$ denote to all problem variables.

For each generator scheduled for maintenance, a binary variable (X_{gt}) is defined as a binary variable in (2) that determines the starting time of the maintenance. Likewise, Y_{lt} is defined as a binary variable for each transmission line scheduled for maintenance that determines the starting transmission line maintenance time interval as imposed in (3). In (4), Z_{lt} are binary variables indicate the statuses of the switchable lines, ie, 0 for open and 1 for closed. Note that the scheduled statuses of the switchable lines do not change in the base case and contingencies.

$$X_{gt} \in \{0,1\} \qquad \forall g \in G_m, \forall t \tag{2}$$

$$Y_{lt} \in \{0,1\} \qquad \forall l \in L_m, \forall t \tag{3}$$

$$Z_{lt} \in \{0,1\} \qquad \forall l \in L_s, \forall t \tag{4}$$

Constraints (5) and (6) ensure that the maintenance of the generators and the transmission lines are started within the scheduling horizon respectively.

$$\sum_t X_{gt} = 1 \qquad \forall g \in G_m \tag{5}$$

$$\sum_t Y_{lt} = 1 \qquad \forall l \in L_m \tag{6}$$

To make sure that the maintenance of the generators and transmission lines is finished in the planning horizon, X_{gt} and Y_{gt} as binary variables denote the starting maintenance periods of the generators and transmission lines are set to zero for time intervals greater than or equal to $|T| - MD_{g/l} + 1$ in (7) and (8) respectively. If the maintenance of a generating unit or transmission line starts at the beginning of time interval $|T| - MD_{g/l} + 1$, it will be finished at the beginning of time interval $|T| - MD_{g/l} + 1 + MD_{g/l} = |T| + 1$ or at the end of the time interval $|T|$. Therefore, time interval $|T| - MD_{g/l} + 1$ is the last time interval that the maintenance can be started and finished in the planning horizon.

$$X_{gt} = 0 \qquad \forall g \in G_m, \forall t \geq \left(|T| - MD_g + 1\right) \tag{7}$$

$$Y_{lt} = 0 \qquad \forall l \in L_m, \forall t \geq \left(|T| - MD_l + 1\right) \tag{8}$$

The output of each generation unit not due for maintenance is defined as a positive variable which is limited by its capacity $(\overline{P}_g)$ and its contingency state (U_g^c) as mathematically expressed in (9).

$$0 \leq P_{gt}^c \leq U_g^c \cdot \overline{P}_g \qquad \forall g \in G_{nm}, \forall t, \forall c \tag{9}$$

The output of each generation unit due for maintenance is defined as a positive control variable which is limited by its capacity $(\overline{P}_g)$ and its contingency state U_g^c and is also influenced by its maintenance status as stated in (10). The output of each generation unit due for maintenance is also influenced by its maintenance status. Thus, because the generation unit maintenance decision variable X_{gt} denotes to the maintenance starting time not the unit is under maintenance or not, it is needed to determine starting maintenance at which time interval results in maintenance of the unit in time interval$t$. For this aim, we define operator $\langle g, t \rangle = \max(1, t - MD_g + 1)$ which determines the first time interval that if the maintenance of unit g starts, the unit will be in maintenance in time interval t. In other words, the unit g will be in maintenance if the maintenance starts at each of time intervals $\langle g, t \rangle$ to t. Thus, the maintenance starting time statuses are summed over these time interval $\sum_{\tau=\langle g,t \rangle}^{t} X_{g\tau}$ to determine that whether the unit is under maintenance or not. The value of $\sum_{\tau=\langle g,t \rangle}^{t} X_{g\tau}$ is equal to 1 when the unit is under maintenance and the output of the unit is 0.

$$0 \le P_{gt}^{c} \le \left(1 - \sum_{\tau=\langle g,t\rangle}^{t} X_{g\tau}\right) \cdot U_g^c \cdot \overline{P}_g \ \forall g \in G_m, \forall t, \forall c \tag{10}$$

Constraints (11) state that the outputs of generation units should not be changed when the forced outage of a transmission line is the contingency, which is a preventive approach in modeling transmission line failure. In other words, the constraints (11) result in a schedule which does not violate from postcontingency boundaries, and thus, no corrective action is needed to eliminate violation. Constraints (12) limit the difference between postcontingency and normal outputs of units to their down and up ramp rates when the forced outage of a transmission line is the contingency.

$$P_{gt}^{c} = P_{gt}^{n} \quad \forall g, \forall t, \forall c \in C_l \tag{11}$$

$$P_{gt}^{n} - RD_g \le P_{gt}^{c} \le P_{gt}^{n} + RU_g \quad \forall g, \forall t, \forall c \in C_g \tag{12}$$

The voltage phase angles and phase shifting transformer angles are restricted in (13) and (14) respectively.

$$\theta^{\min} \le \theta_{bt}^{c} \le \theta^{\max} \quad \forall b, \forall t, \forall c \tag{13}$$

$$\delta^{\min} \le \delta_{lt}^{c} \le \delta^{\max} \quad \forall l \in L_{PST}, \forall t, \forall c \tag{14}$$

The reserve constraint is defined in (15) which states that the available generation capacity should be greater than or equal to multiplication of the each time interval load and 1 plus the reserve rate. Reserve rate may be defined as a percentage of load to cope with demand fluctuation.

$$\sum_{\forall g \in G_m} \left(1 - \sum_{\tau=\langle g,t\rangle}^{t} X_{g\tau}\right) \cdot U_g^c \cdot \overline{P}_g + \sum_{\forall g \in G_{nm}} U_g^c \cdot \overline{P}_g \ge DL_t \cdot (1+R) \quad \forall t, \forall c \tag{15}$$

The nodal balance is enforced in (16), in which the left-hand side of each equation is the bus injection, ie, generation minus demand, and its right-hand side is the power flows from and to the bus respectively. The nodal balance equations are written for both normal ($c = 0$) and contingency cases ($\forall c \ge 1$).

$$\sum_{\forall g \in G_b} P_{gt}^{c} - D_{bt} = \sum_{\forall l \in L_b^f} F_{lt}^{c} - \sum_{\forall l \in L_b^t} F_{lt}^{c} \ \forall b, \forall t, \forall c \tag{16}$$

The transmission lines can be classified into switchable and nonswitchable on the one hand and lines assumed and not assumed to be maintained on the other hand, which result in 4 categories. The relation between the power flows and voltage angles are modeled for these 4 line categories in (17) to (20). The value of M_l is set to $(\theta^{\max} - \theta^{\min})/x_l$ according to Zhang et al,[3] Hedman,[10] and Hedman et al.[13] Similar with generation units, the summation over time $\langle l, t\rangle$, which is defined as $\max(1, t - MD_l + 1)$, to time t is used to determine the lines which are under maintenance in time interval t in (19) and (20).

$$\left|F_{lt}^{c} - A_{lt}^{c}\right| \le M_l \cdot \left(1 - U_l^c\right) \forall l \in (L_{nm} \cap L_{ns}), \forall t, \forall c \tag{17}$$

$$\left|F_{lt}^{c} - A_{lt}^{c}\right| \le M_l \cdot \left(2 - U_l^c - Z_{lt}\right) \forall l \in (L_{nm} \cap L_{s}), \forall t, \forall c \tag{18}$$

$$\left|F_{lt}^{c} - A_{lt}^{c}\right| \le M_l \cdot \left(1 - U_l^c + \sum_{\tau=\langle l,t\rangle}^{t} Y_{l\tau}\right) \forall l \in (L_{m} \cap L_{ns}), \forall t, \forall c \tag{19}$$

$$\left|F_{lt}^{c} - A_{lt}^{c}\right| \le M_l \cdot \left(2 - U_l - Z_{lt} + \sum_{\tau=\langle l,t\rangle}^{t} Y_{l\tau}\right) \forall l \in (L_{m} \cap L_{s}), \forall t, \forall c \tag{20}$$

The auxiliary variable A_{lt}^{c} is defined for transmission lines with and without phase shifting transformer in (21) and (22) respectively.

$$A_{lt}^{c}=\frac{\theta_{fr(l),t}^{c}-\theta_{to(l),t}^{c}+\delta_{l,t}^{c}}{\left(x_{l}+x_{l}^{PST}\right)}\qquad\forall l\in L_{PHS},\forall t,\forall c\tag{21}$$

$$A_{lt}^{c}=\frac{\theta_{fr(l),t}^{c}-\theta_{to(l),t}^{c}}{x_{l}}\quad\forall l\in L_{nPHS},\forall t,\forall c\tag{22}$$

The power flows of all transmission lines are limited to their maximum flows times their contingency statuses in (23). The power flow of lines with phase shifting transformers should be limited to the maximum flows of them (24). Moreover, the power flows of switchable lines and due for maintenance lines are restricting in (25) and (26) respectively.

$$\left|F_{lt}^{c}\right|\leq\overline{F}_{l}^{c}\cdot U_{l}^{c}\quad\forall l,\forall t,\forall c\tag{23}$$

$$\left|F_{lt}^{c}\right|\leq\overline{F}_{l}^{PST}\quad\forall l\in L_{PST},\forall t,\forall c\tag{24}$$

$$\left|F_{lt}^{c}\right|\leq\overline{F}_{l}^{c}\cdot Z_{lt}\quad\forall l\in L_{s},\forall t,\forall c\tag{25}$$

$$\left|F_{lt}^{c}\right|\leq\overline{F}_{l}^{c}\cdot\left(1-\sum_{\tau=\langle l,t\rangle}^{t}Y_{l\tau}\right)\quad\forall l\in L_{m},\forall t,\forall c\tag{26}$$

The GTEMSTS problem is modeled for power systems with integrated structure to concentrate on the effects of TS on GTEMS problem regardless of the restrictions and impacts of restructured power system. However, the proposed model can be adapted for restructured power system. The resulting GTEMSTS is a large-scale MILP optimization problem. Although this problem can be solved by the off-the-shelf commercial optimization solvers, it may needs enormous memory and CPU time requirements. A decomposition based solution approach will be provided in the next section.

3 | DECOMPOSITION APPROACH

The decomposition approach of Hedman et al[13] is used in this paper for solving the GTEMSTS problem. This decomposition approach is successfully applied to optimal day-ahead unit commitment and transmission switching in Hedman et al,[13] in which the N-1 reliable unit commitment problem is solved firstly. Then, the problem is solved with fixed unit commitment status variables, which results in transmission switching statuses. This process continues repeatedly until either the unit commitment and transmission switching variables do not change or the solution time window exhausted. In this paper, the GTEMSTS problem is separated into 2 subproblems: GTEMS subproblem and TS subproblem. The first subproblem is GTEMS subproblem (27) to (31) in which all transmission switching variables are replaced with fixed preset parameters ($\overline{Z}_{lt}$).

GTEMS subproblem:

$$\min_{\boldsymbol{\Omega}_{GTEMS}}\quad OF_{GTEMS}=\left(\begin{array}{c}\sum\limits_{\forall g\in G_{m},\forall t}H_{gt}\cdot X_{gt}+\\ \sum\limits_{\forall l\in L_{m},\forall t}H_{lt}\cdot Y_{lt}+\\ \sum\limits_{\forall g,\forall t}c_{g}\cdot DT_{t}\cdot P_{gt}^{n}\end{array}\right)\tag{27}$$

Subject to:

$$(2),(3),(5)\text{ to }(17),(19),(23),(26)\tag{28}$$

$$\left|F_{lt}^{c}-\frac{\theta_{fr(l),t}^{c}-\theta_{to(l),t}}{x_{l}}\right|\leq M_{l}\cdot\left(2-U_{l}^{c}-\overline{Z}_{lt}\right)\quad\forall l\in(L_{nm}\cap L_{s}),\forall t,\forall c \tag{29}$$

$$\left|F_{lt}^{c}-\frac{\theta_{fr(l),t}^{c}-\theta_{to(l),t}}{x_{l}}\right|\leq M_{l}^{c}\cdot\left(2-U_{l}-\overline{Z}_{lt}+\sum_{\tau=\langle l,t\rangle}^{t}Y_{l\tau}\right)\quad\forall l\in(L_{m}\cap L_{s}),\forall t,\forall c \tag{30}$$

$$\left|F_{lt}^{c}\right|\leq\overline{F}_{l}^{c}\cdot\overline{Z}_{lt}\quad\forall l\in L_{s},\forall t,\forall c \tag{31}$$

where $\mathbf{\Omega}_{GTEMS}=\mathbf{\Omega}\{Z_{lt},\forall l\in L_{s},\forall t\}$.

In the first iteration, the transmission switching variables are set to 1 ($\overline{Z}_{lt}=1$), ie, all lines are connected. Once the GTEMS problem is solved, then the second subproblem is solved. The second subproblem is TS subproblem (32) to (37). To obtain TS subproblem, the maintenance starting time variables, ie, X_{gt} and Y_{lt}, are removed and substituted by fixed preset values $\overline{X}_{gt}$ and $\overline{Y}_{lt}$ respectively. Moreover, the constraints which are defined over only maintenance variables are omitted from the GTEMSTS model.

TS subproblem:

$$\min_{\mathbf{\Omega}_{\mathrm{TS}}}\quad OF_{\mathrm{TS}}=\begin{pmatrix}\sum\limits_{\forall g\in G_{m},\forall t}H_{gt}\cdot\bar{X}_{gt}+\\ \sum\limits_{\forall l\in L_{m},\forall t}H_{lt}\cdot\bar{Y}_{lt}\quad+\\ \sum\limits_{\forall g,\forall t}c_{g}\cdot DT_{t}\cdot P_{gt}^{n}\end{pmatrix} \tag{32}$$

Subject to:

$$(4),(9),(11)\text{ - }(18),(23)\text{ - }(25) \tag{33}$$

$$0\leq P_{gt}^{c}\leq\left(1-\sum_{\tau=\langle g,t\rangle}^{t}\overline{X}_{g\tau}\right)\cdot U_{g}^{c}\cdot\overline{P}_{g}\forall g\in G_{m},\forall t,\forall c \tag{34}$$

$$\left|F_{lt}^{c}-\frac{\theta_{fr(l),t}^{c}-\theta_{to(l),t}}{x_{l}}\right|\leq M_{l}\cdot\left(1-U_{l}^{c}+\sum_{\tau=\langle l,t\rangle}^{t}\overline{Y}_{l\tau}\right)\quad\forall l\in(L_{m}\cap L_{ns}),\forall t,\forall c \tag{35}$$

$$\left|F_{lt}^{c}-\frac{\theta_{fr(l),t}^{c}-\theta_{to(l),t}}{x_{l}}\right|\leq M_{l}^{c}\cdot\left(2-U_{l}-Z_{lt}+\sum_{\tau=\langle l,t\rangle}^{t}\overline{Y}_{l\tau}\right)\quad\forall l\in(L_{m}\cap L_{s}),\forall t,\forall c \tag{36}$$

$$\left|F_{lt}^{c}\right|\leq\overline{F}_{l}^{c}\cdot\left(1-\sum_{\tau=\langle l,t\rangle}^{t}\overline{Y}_{l\tau}\right)\quad\forall l\in L_{m},\forall t,\forall c \tag{37}$$

where $\mathbf{\Omega}_{\mathrm{TS}}=\mathbf{\Omega}\left\{X_{gt},\forall g\in G_{m},\forall t;\quad Y_{lt},\forall l\in L_{m},\forall t\right\}$.

Note that at least 1 solution exists for TS subproblem, ie, the solution with the states of the transmission lines in the GTEMS subproblem at the current iteration. Similarly, at least 1 solution exists for the GTEMS subproblem which is the solution with the maintenance statuses of the previous iteration's TS subproblem. Therefore, if a maintenance schedule exists without taking TS into account, the GTEMS subproblem at the first iteration is feasible, and thus, according to the mentioned reason, all GTEMS and TS subproblems will be feasible.

If the switching states of the transmission lines do not change over 2 consecutive iterations, the algorithm is converged. In this situation, on the one hand, the last maintenance schedule is the best schedule for the last obtained switching schedule, and on the other hand, the last switching schedule is the best schedule for the last obtained maintenance schedule. Thus, both maintenance and transmission schedules will not be altered if the algorithm continues or in other words the algorithm converges. The algorithm continues to global optimality if the mentioned stopping criterion is used. Other methods may be used as stopping criteria. If the objective function of TS subproblem changes slowly, the algorithm could be stopped. This criterion can be defined as $\left(OF_{TS}^{k}-OF_{TS}^{k-1}\right)/OF_{TS}^{k}\leq\varepsilon$, where OF_{TS}^{k} is the value of TS subproblem objective function at iteration k and ε is a small value, eg, 10^{-5}.

The decomposition algorithm for solving GTEMSTS problem is as follows:

Step 0. Set all transmission lines closed ($\overline{Z}_{lt}=1$) and fix the iteration counter to $1(k=1)$.

Step 1. Solve the GTEMS subproblem and obtain solution (X_{gt}^{*} and Y_{lt}^{*}). Fix maintenance statuses, ie, $\overline{X}_{gt}=X_{gt}^{*}$ and $\overline{Y}_{lt}=Y_{lt}^{*}$.

Step 2. Solve the TS subproblem and obtain solution (Z_{lt}^{*}) and TS subproblem objective function (OF_{TS}^{*}). Fix TS statuses ($\overline{Z}_{lt}=Z_{lt}^{*}$). Save objective function value ($OF_{\mathrm{TS}}^{k}=OF_{\mathrm{TS}}^{*}$) and TS statuses ($Z_{lt}^{k}=Z_{lt}^{*}$).

Step 3. If $k>1$ and $Z_{lt}^{k}=Z_{lt}^{k-1}$, return ($\overline{X}_{gt}, \overline{Y}_{lt}$, and $\overline{Z}_{lt}$) and terminate. Otherwise, update iteration counter $k\leftarrow k+1$ and continue with step 1.

If a decision maker prefers to use the relative difference of objective values over 2 consecutive iterations, $Z_{lt}^{k}=Z_{lt}^{k-1}$ should be substituted by $\left(OF_{TS}^{k}-OF_{TS}^{k-1}\right)/OF_{TS}^{k}\leq\varepsilon$ in step 3 of the algorithm. The flow chart of decomposition approach is presented in Figure 1.

4 | CUMPUTATIONAL EXPERIMENTS

4.1 | Case study

The proposed GTEMSTS model and the decomposition method are tested on IEEE 30-bus test system.[21,22,41] The IEEE 30-bus has 6 generation units and 41 transmission lines, which is depicted in Figure 2. Generation unit 2 and transmission lines 6-8, 6-9, 18-19, and 27-29 are scheduled for maintenance. The maintenance duration of these due for maintenance components are 7, 6, 5, 6, and 5 days respectively. In addition, all transmission lines are considered switchable, and all generation units and all transmission lines except lines 27-30, 29-30, 10-20, 15-18, 19-20, 14-15, and 25-26 are considered in the N-1 contingency list. Note that the transmission lines which are omitted from N-1 list are either radial lines or they become radial when a due for maintenance line is in its scheduled outage. A phase shifting transformer is installed in line between busses 9 and 10. The minimum and maximum phase angles, capacity, and reactance of all phase shifting transformers are −10° and 10°, 100 MW, and 0.018 per unit respectively. All MILP problems are solved by CPLEX[42] solver under GAMS modeling environment.[43] The maintenance planning horizon is 1 month, and the resolution of time intervals is a day. The maintenance cost of all generation units and transmission lines are $24k and $96k respectively, for each day of maintenance. The problem is solved for March. The daily system demand across March is shown in Figure 3.[44] The demand is high at the beginning of the weeks, eg, days 6, 13, 20, and 27, and decreases across the weeks. The system peak demand over the month under study happens on day 6. Moreover, the initial maintenance schedule of generation and transmission equipment is shown in Table 1.

4.2 | Results and analysis

The size of GTEMS and GTEMSTS problems, with and without N-1 security criterion, is listed in Table 2. In this table, the numbers of continuous and binary variables and the numbers of constraints are provided in the separate columns. According to Table 2, incorporate N-1 security criterion in both GTEMS and GTEMSTS increases the number of constraints and continuous variables. The solution time of optimization GTEMS and GTEMSTS models is given in Table 3. As presented in this table, the GTEMSTS model in both with N-1 and without N-1 security is not solved in an hour. In the GTEMSTS problem, the maintenance schedule binds time intervals together on the one hand and TS variables connect the normal and contingency states on the other hand, whereas separating of GTEMS and TS problems in the proposed decomposition method decreases the computational burden. Therefore by considering decomposition method, the GTEMSTS problems are solved in 32 and 1372 seconds, and converged in 3 iterations, in normal and contingency states. Additionally, transmission switching increases solution computational times in secure and unsecure GTEMS problem which in normal state is 32 and in contingencies state is 5.76 times.

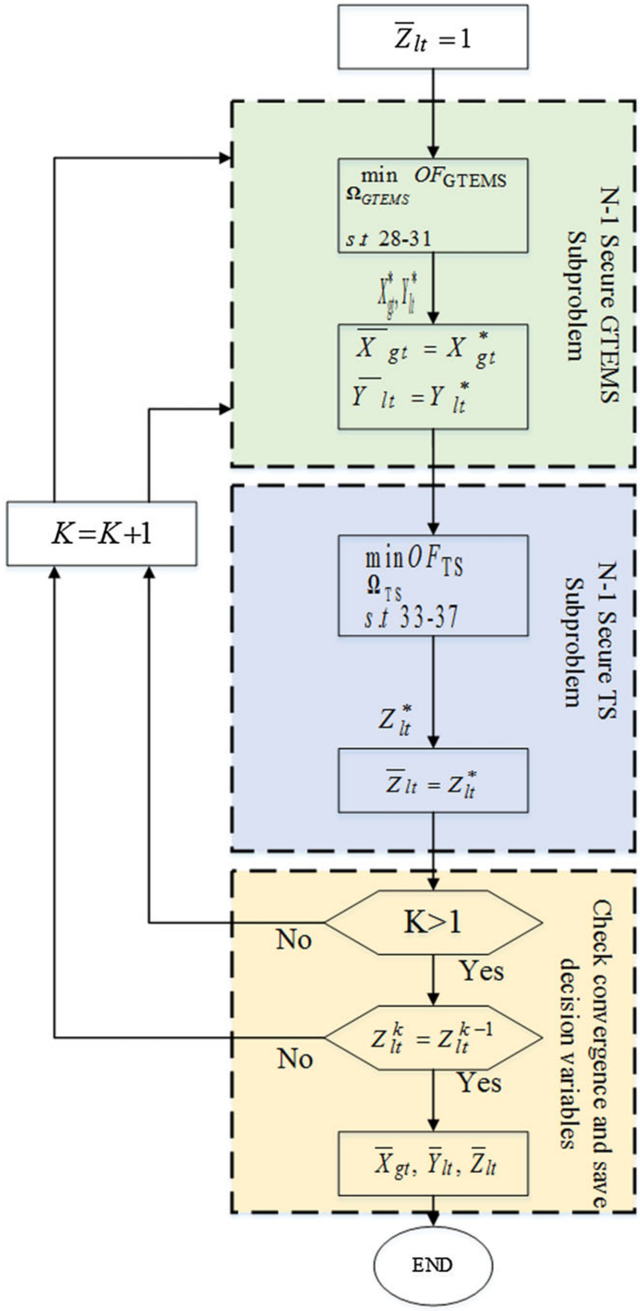

FIGURE 1 Flowchart of decomposition approach

The maintenance schedule cost during March is provided in Table 4. Cost saving is compared within 3 terms of TS cost saving, PST cost saving, and total cost saving. Transmission switching cost saving is calculated when PST is not taken account, whereas PST cost saving is calculated when TS is not taken into account and total cost saving is calculated in the presence of PST and TS at the same time in comparison of base case (PST and TS are not taken account). The maintenance schedule cost for GTEMS and maintenance schedule cost for GTEMSTS in the presence of PST are \$5 827 663 and \$5 730 249 for with N-1 security criterion respectively. Also these costs without considering security are \$5 395 133 and \$4 963 324 respectively. Accordingly, using transmission switching and PST reduces the total system cost by 10.1% in no security case, and it decreased by 2.5% when N-1 security criterion is taken into account. The main reason of this observation is that to keep system secure, the number of lines which can open is extremely reduced. In other words, although the opening of the transmission lines leads to the cost savings in the normal state, this may cause load curtailment in contingency states. Note that the obtained results are consistent with the other TS studies such as Hedman et al,[10] in which adding N-1 security constraints shrinks the cost saving.

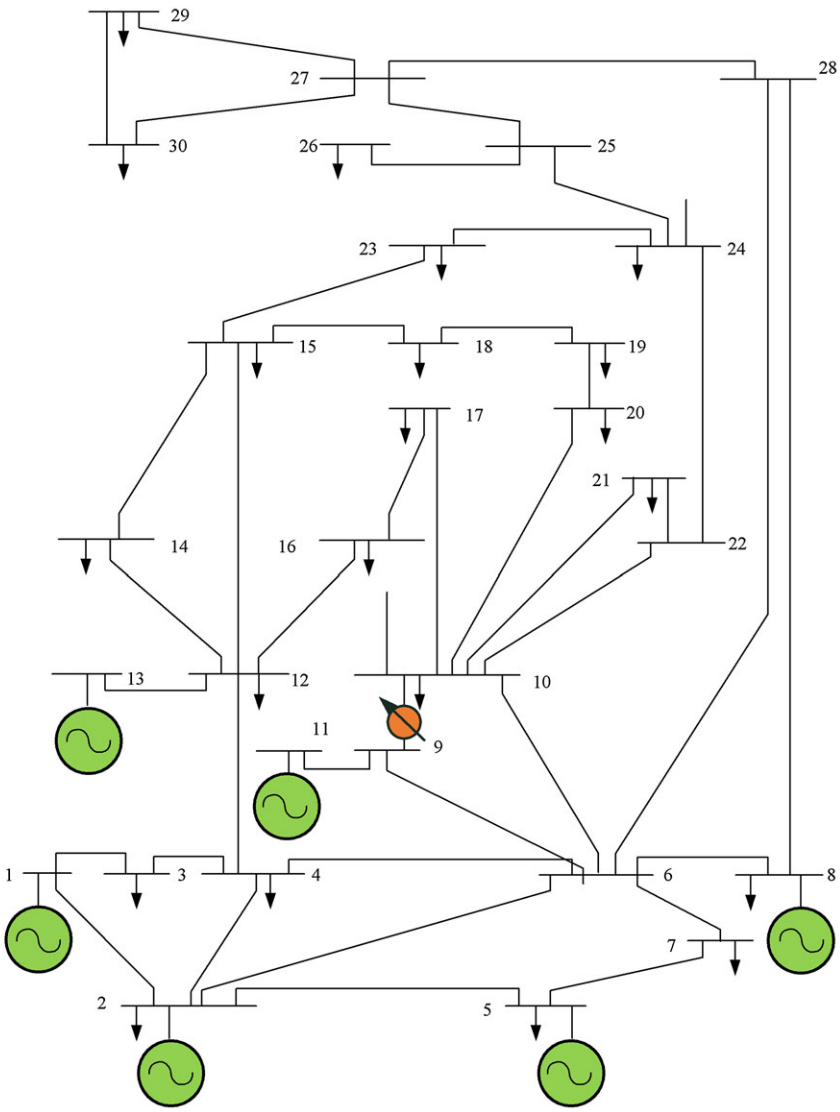

FIGURE 2 The IEEE 30-bus test system

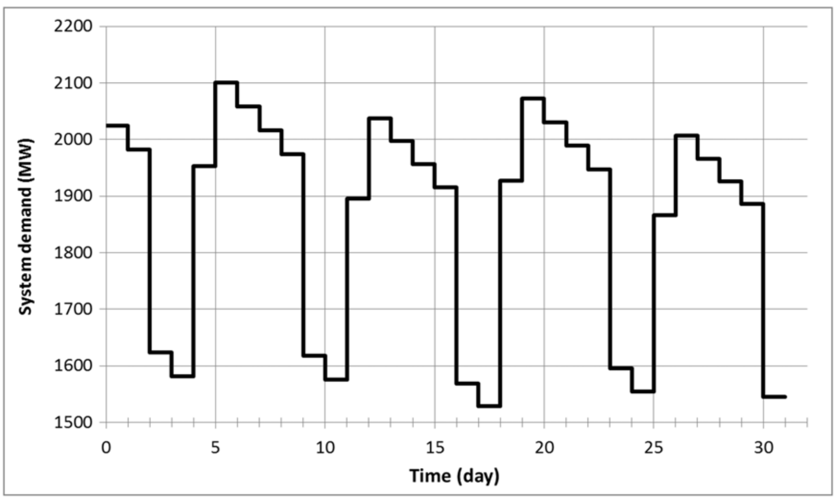

FIGURE 3 Daily system demand of IEEE 24-bus RTS in march

The statuses of 6 switchable lines are shown in Tables 5 and 6. The most visible observation in these tables is that more lines remain in service to maintain the security of the power system. In the without N-1 security criterion, line 12-13 is always open, whereas this line is open in significantly lower time periods in with N-1 security criterion. On the

TABLE 1 The initial maintenance schedule

Equipment	Initial Scheduling Start Time	Initial Scheduling End Time
Gen 2	7	13
Lines 6-8	19	24
Lines 6-9	17	21
Lines 18-19	2	7
Lines 27-29	11	15

TABLE 2 The size of the optimization problems

		Without Transmission Switching	With Transmission Switching
Without N-1 security criterion	No. of continuous variables	3783	3783
	No. of binary variables	150	1380
	No. of constraints	9662	12 152
With N-1 security criterion	No. of continuous variables	148 953	148 953
	No. of binary variables	150	1380
	No. of constraints	415 352	516 242

TABLE 3 The solution times of the optimization problems

N-1 Security Criterion	Decomposition	Without TS (seconds)	With TS (seconds)	Ratio
No	No	1	-	
	Yes	1	32	32
Yes	No	238	-	
	Yes	238	1372	5.76

TABLE 4 Cost saving of TS and PST considering N-1

N-1	PST	Without TS ($)	With TS ($)	TS Cost Saving	PST Cost Saving	Total Cost Saving
No	No	5 519 221	5 246 233	8.7	5.7	10.1
	Yes	5 395 133	4 963 324			
Yes	No	5 880 111	5 776 090	1.7	0.8	2.5
	Yes	5 827 663	5 730 249			

TABLE 5 The switching states of 6 switchable transmission lines without N-1 security criterion

Day Line	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
6-8	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6-10	0	0	0	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	0	1	1	1	1	1
9-11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9-10	1	1	1	1	0	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
12-13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18-19	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1

TABLE 6 The switching states of the switchable transmission lines with N-1 security criterion

Day Line	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
6-8	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6-10	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1
9-11	0	0	1	0	1	0	1	0	0	0	0	0	1	0	1	0	0	1	1	1	0	1	1	0	0	0	1	0	1	0	0
9-10	1	1	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
12-13	1	0	1	1	1	1	1	0	0	0	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1	0	0	1
18-19	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1

other hand, line 18-19 is open in more time periods in the with N-1 security criterion compared with the without security criterion one.

The outage schedule of generation units in the both unsecure GTEMS and GTEMSTS models is shown in Figure 4. Also, the schedule outage of generation units in the secure GTEMS and GTEMSTS models is shown in Figure 5. Deep looking on these figures shows that by adding the N-1 criterion, the schedule outage of generation units is changed. An important observation from these figures is that adding TS to the models changes the optimal maintenance schedule in both secure and unsecure ones. Note that the topology of the transmission system is changed by adding TS and affected not only the optimal power flow but also the maintenance schedule of the generation and transmission equipment. Moreover, similar to Zhu et al,[22] the optimal maintenance schedule of the transmission and generation equipment is different with the initial schedule which is shown in Table 1.

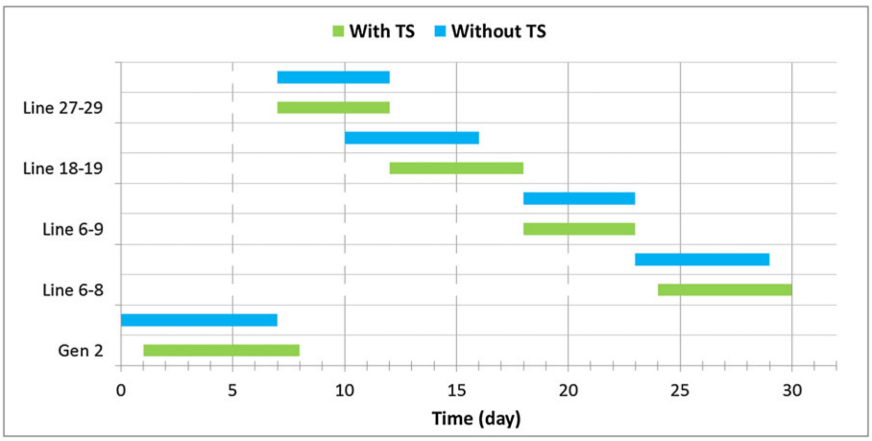

FIGURE 4 Maintenance scheduling without N-1 security criterion and with and without TS

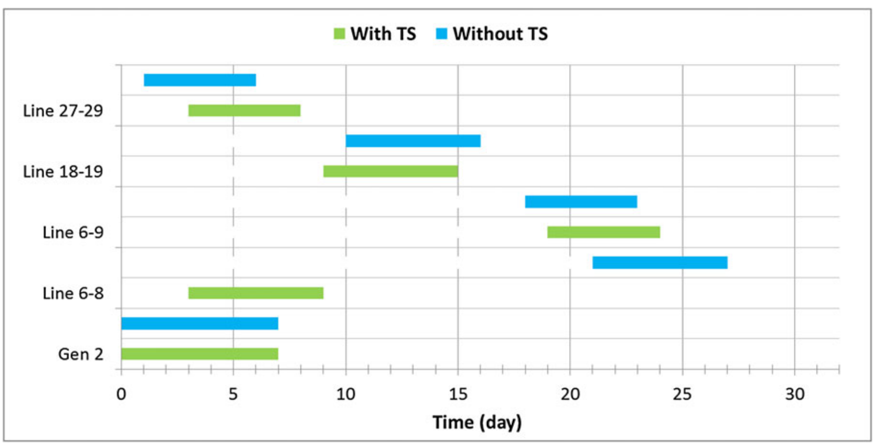

FIGURE 5 Maintenance scheduling with N-1 security criterion and with and without TS

5 | CONCLUSION

This paper presents a model for the GTEMSTS in a power system with the presence of PST as a FACTS device. The power flow of the PST-located lines is changed, which will change the transmission system power flow. Adding both TS and PST to transmission system can increase the flexibility of it. However, TS may decrease the system security by switching transmission lines out. Thus, the N-1 criterion is added to model the security. The resulting problem is a mixed integer linear program, in which the scheduling time intervals and contingency states are linked by maintenance schedule and transmission switching variables respectively. In the proposed decomposition solution strategy, the GTEMSTS problem is separated into 2 GTEMS and TS subproblems to address the computational burden. The proposed GTEMSTS model and decomposition method are tested on the IEEE 30-bus test system. The GTEMSTS problem with and without N-1 security criterion is not solved in an hour, while the decomposition method converged in less than 30 minutes. Cost savings in unsecure and secure N-1 GTEMSTS are 10.1% and 2.5%, respectively. Adding N-1 security criterion to the GTEMSTS model reduces the number of transmission switching and keeps more lines in service which results in a higher reliability and lower cost saving during maintenance horizon. The most important observation is that incorporating TS into the GTEMS changes the maintenance schedule by modifying the topology of the transmission system and the modified topology brings the possibility of using low-cost generation units. The proposed model can be extended by adding more FACTS devices such as thyristor controlled series capacitor devices.

NOMENCLATURE

Indices

g	Index for generating unit.
l	Index for transmission line.
b	Index for bus.
t	Index for time interval.
c	Index for normal, $c = 0$, and contingency states, $c \geq 1$.

Sets

G	Set of all generating units.
G_m, G_{nm}	Set of generating units which are (not) supposed to be maintained.
G_b	Set of generating units at bus b.
L	Set of all transmission lines.
L_m (L_{nm})	Set of transmission lines which are (not) supposed to be maintained.
L_s (L_{ns})	Set of switchable (nonswitchable) transmission lines.
$L_b^{f/t}$	Set of transmission lines from/to bus b.
T	Set of time intervals which form the study planning horizon.
C_g (C_l)	Set of contingency states corresponding to generation unit (transmission line) failures.
L_{PST} (L_{nPST})	Set of lines with (without) phase shifting transformers.
$\mathbf{\Omega}$	Set of all variables of the GTEMSwTS problem.
$\mathbf{\Omega}_{GTEMS}$	Set of all variables of the GTEMS subproblem.
$\mathbf{\Omega}_{\mathrm{TS}}$	Set of all variables of the TS subproblem.

Parameters

DT_t	Duration of time interval t.
H_{gt}	Maintenance cost of unit gin time interval t.
H_{lt}	Maintenance cost of line l in time interval t.
c_g	Production cost of unit g.
U_g^c	Contingency state of unit g in state c.
U_l^c	Contingency state of line l in state c.
$\overline{F}_l^n$	Maximum power flow of line l in the normal state.
$\overline{F}_l^c$	Maximum power flow of line l in contingency states.
$\overline{F}_l^{PST}$	Maximum power flow of phase shifting transformer installed at line l.
$\overline{P}_g$	Maximum power output of unit g.

DL_t	System demand in time interval t.
D_{bt}	Demand of bus b in time interval t.
R	System reserve rate.
MD_g	Maintenance duration of unit g.
MD_l	Maintenance duration of line l.
BM_l	Big disjunctive constant value.
x_l	Reactance of line l.
x_l^{PST}	Reactance of phase shifting transformer installed at line l.
$\theta^{\min}$, $\theta^{\max}$	Minimum and maximum voltage phase angle.
$\delta_l^{\min}$, $\delta_l^{\max}$	Minimum and maximum phase shifting angle installed at line l.
OF_{GTEMS}^k	The value of objective function of GTEMS subproblem at iteration k.
OF_{TS}^k	The objective function value of TS subproblem at iteration k.
$\overline{X}_{gt}$	Preset fixed status of generation unit g at the beginning of time interval t, 1 if the unit maintenance starts and 0 otherwise.
$\overline{Y}_{lt}$	Preset fixed status of transmission line l at the beginning of time interval t, 1 if the line maintenance starts and 0 otherwise.
$\overline{Z}_{lt}$ (Z_{lt}^k)	Preset fixed status of transmission line l in time interval t(at iteration k), 1 if the line is closed and 0 otherwise.
ε	A small value.

Variables

X_{gt}	Binary decision variable that is equal to 1 if maintenance of unit g starts at the beginning of time interval t and 0 otherwise.
Y_{lt}	Binary decision variable that is equal to 1 if maintenance of transmission line l starts at the beginning of time interval t and 0 otherwise.
Z_{lt}	Switching status of transmission line l in time interval t which is equal to 1 if line l is closed and 0 otherwise.
P_{gt}^c	Generation of unit g in time interval t and contingency state $c \geq 1$.
P_{gt}^n	Generation of unit g in time interval t and normal state ($c = 0$).
F_{lt}^c	Power flow of line l in time t and contingency state c.
A_{lt}^c	Auxiliary variable for line l in time t and contingency state c.
θ_{bt}^c	Voltage phase angle of bus b in time t and contingency state c.
δ_{lt}^c	Phase shifting angle of bus l in time t and contingency state c.
OF_{GTEMS}	The objective function value of GTEMS subproblem.
OF_{TS}	The objective function value of TS subproblem.

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