Transmission Switching in Security-Constrained Unit Commitment

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***Abstract*— Transmission switching (TS) is introduced in security-constrained unit commitment (SCUC) for alleviating transmission violations and reducing the operating cost. The SCUC problem is decomposed into a UC problem and a TS problem. The UC problem finds the optimal hourly schedule of generating units. The TS problem uses this solution for transmission switching to find the optimal dispatch of units when considering network constraints. This TS problem also examines contingencies and identifies required changes to the UC problem solution when contingencies cannot be mitigated in the TS problem. The case studies exhibit the effectiveness of the proposed approach.**

***Index Terms*— Transmission switching, Security-constrained unit commitment, Mixed-integer, Benders decomposition.**

NOMENCLATURE

b	Index for bus.
c	Index for contingency.
F_{ci}	Production cost function of unit i.
i	Index for unit.
I_{it}	Commitment state of unit i at time t.
l	Index for line.
L_b	Set of lines connected to bus b.
n	Index for iterations.
NB	Number of buses.
NC	Number of contingencies
NL	Number of lines.
NG	Number of units.
NS	Number of switchable lines.
NNS	Number of non-switchable lines.
NT	Number of time periods.
$P_{D,t}$	System demand at time t.
P_{bt}	Power injection at bus b at time t.
P_{it}	Generation of unit i at time t.
$P_{i,\min}$	Minimum power generation of unit i.
$P_{i,\max}$	Maximum power generation of unit i.
PL_{lt}^{ns}	Power flow on non-switchable line l at time t.
PL_{lt}^{s}	Power flow on switchable line l at time t.
$PL_{l,\max}$	Maximum capacity of line l.
$SL_{b,1}, SL_{b,2}$	Slack variables for power mismatch at bus b.
t	Index for time.
W_{it}^{c}	Contingency state of unit i at time t in contingency c.
x_l	Reactance of line l.
Y_{lt}^{c}	Contingency state of line l at time t in contingency c.
z_{lt}	Switching state of line l at time t.
π_{it}^{n}	Marginal change in violations with increase in unit i generation at time t in the nth iteration.
δ_{mt}	Phase angle of bus m at time t.
$\delta_{mn}^{\max}$	Maximum standing phase angle difference between buses m and n.

I. INTRODUCTION

ONE approach to maintain the transmission security and relieve transmission flow violations is to switch power system elements. Corrective transmission switching (TS) can provide economical benefits when compared with other control methods such as generation unit rescheduling or load shedding [1,2]. In [3], TS was considered by applying current sources at bus terminals of certain elements in the base network. The injected currents are control variables in the optimal TS problem. In [4] switching was employed as a corrective action to mitigate contingencies. Also, it is used to model outages in the optimal power flow. In [5] a method was devised for calculating N-1 secure states by TS. A linear switching model was applied to model control actions applied to contingency constraints. In [6], TS was considered as a means of relieving violations in transmission flows and bus voltages. Also, practical issues related to switching operations were addressed. In these papers, transformers tap adjustments and static VAR compensators were recognized as a means of controlling voltage problems [6]. In [7] an algorithm is developed for switching off lines and buses to relieve contingencies. This algorithm is based on a sparse inverse technique and fast decoupled power flow.

These works showed that switching provides flexible control actions for voltage stability, congestion management, loss reduction, cost minimization and system security. In [8] the TS problem is considered for providing system operators with a congestion management tool. In [9] the problem of finding an optimal generation dispatch and transmission topology is a mixed-integer linear program which employs

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binary variables to represent the equipment state. The paper found that large improvements in dispatch cost were achieved by TS. [10] is an extension to [9] which demonstrates that market participants are subject to system uncertainties when considering TS. It presents how topology changes affect nodal prices, load payments, generation revenues, congestion costs, and flowgate prices.

The main difficulty in such approaches is to deal with discrete control variables in real-time. This problem is alleviated in [9] by using mixed-integer programming (MIP). Obviously, the optimal solution for relieving an overload situation is to obtain a SCUC solution that takes into account temporal generating unit and transmission network constraints. The real-time solution would represent a major computational burden in power system operation.

Fig. 1 depicts the hierarchy for calculating SCUC using TS. The proposed SCUC model consists of UC and TS problems. Benders decomposition is utilized to decompose the SCUC problem into smaller and easier to solve subproblems [11]-[15].

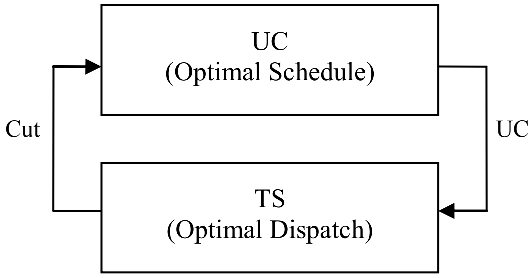

Fig. 1 SCUC using TS

The UC problem has to find the optimal schedule of units, considering the prevailing constraints of UC. The initial optimal schedule of generating units is obtained based on the available market information. Subsequently, the UC solution is used in the TS problem to find the optimal generation of units, considering network security. The switching ability of lines is considered in the TS problem.

TS can be used instead of dc network security in which network violations are minimized in fewer iterations. The TS problem is decomposed into a master problem and a subproblem. The master problem checks the UC result to find whether a feasible TS solution based on the obtained schedule can be found. If the feasibility of the obtained schedule for TS is revealed, the problem will proceed to the subproblem. Otherwise, the network check part will be executed to form benders cut for the next iteration of UC. The network check part examines the network constraints and tries to minimize any violations in the system. If violations persist, proper cuts will be generated and added to the UC problem. In the conventional UC approach, when considering transmission constraints, this iterative process continues until all violations are eliminated and a converged optimal solution is found.

However, in the proposed method, the TS feasibility check part is used to stop the iterative process. The line switching is considered in the TS subproblem. The TS subproblem is an enhanced optimal power flow, which considers the switching ability of lines in the system. Benders decomposition is used to decompose this problem into two smaller subproblems. In case of contingencies, the TS subproblem examines different contingencies and labels them as controllable and uncontrollable. The controllable contingencies are dealt with corrective actions in the TS problem, while the uncontrollable ones are sent back to the UC problem to find a preventive schedule.

One of concerns in performing TS in successive hours is the excessive standing phase angle difference that may exist when closing the lines. Closing a line on a large standing phase angle difference can shock the power system and cause equipment damage or system instability [16]-[18]. In order to avoid unintended closing with a large phase angle difference, breakers are equipped with some relays which prevent closure for angles greater than a preset value. This constraint is modeled is the proposed method.

The rest of the paper is organized as follows. Section II presents the new proposed approach and formulates different parts of it. Section III conducts the numerical simulations and in detail discusses a six-bus system and the IEEE 118-bus system. Finally, concluding remarks are discussed in Section IV.

II. PROBLEM FORMULATION

Fig. 2 depicts the flowchart of this approach. The proposed SCUC model consists of a UC problem and a TS problem. The TS is decomposed into a master problem and a subproblem. In the subproblem, TS is considered via economic dispatch. The solution is used further in the network security check part and proper cuts are formed for economic dispatch and UC. In case of contingencies, this subproblem examines and labels the contingencies as controllable and uncontrollable. The controllable contingencies are handled by corrective actions in the TS problem and the uncontrollable contingencies are dealt with in the UC problem by preventive actions.

A. *UC (Optimal Schedule)*

The objective of UC is to determine the day-ahead schedule of generating units in order to minimize the system operating cost while meeting the prevailing constraints. The objective of UC is composed of fuel costs for producing electric power as well as startup and shutdown costs of each unit over the entire time period. A typical set of constraints of UC includes

- System power balance
- System spinning/operating reserve requirements
- Unit output limits
- Unit spinning/operating reserve limit
- Ramp up/down rate limits
- Minimum up/down time limits
- Fuel limits
- Emission limits

In addition, constraints for uncontrollable unit contingencies are listed as follows.

$$\sum_{i=1}^{NG} P_{it}^{c} = P_{D,t} \qquad (t=1,...,NT)(c=1,...,NC) \qquad (1)$$

$$P_{i,\min} I_{it} W_{it}^{c} \le P_{it}^{c} \le P_{i,\max} I_{it} W_{it}^{c} \qquad (t=1,...,NT)(i=1,...,NG)(c=1,...,NC) \qquad (2)$$

where W^c_{it} is the contingency state of unit i at time t in contingency c. According to (2), whenever the contingency state parameter is zero the generation of the associated unit in that contingency is zero, which means that independent of the unit status in the base case, the unit is out of service in that contingency. In this situation the load balance constraint for each contingency should be satisfied, which is considered by (1). Other unit constraints for considering contingencies may also be added.

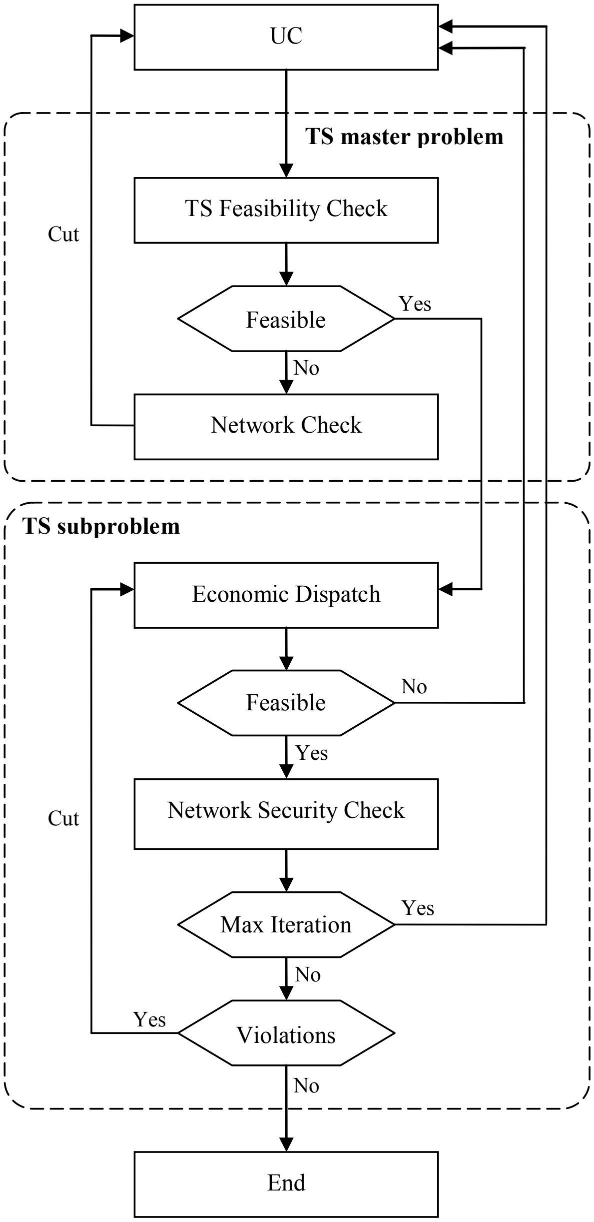

Fig. 2 Flowchart of SCUC using TS

B. *TS Feasibility Check*

The unit commitment state is used in this subproblem to examine a feasible TS solution. The objective is

$$Min \sum_{i=1}^{NG} \sum_{t=1}^{NT} [F_{ci}(P_{it}) * \hat{I}_{it}] \tag{3}$$

This objective is minimize the power production cost. The constraints are bus power mismatch (4), power flow of switchable lines (5)-(8), power flow of non-switchable lines (9)-(11), standing phase angle difference limits (12)-(13), and non-islanding constraint (14).

$$P_{bt} - \sum_{l \in L_b} PL^s_{lt} - \sum_{l \in L_b} PL^{ns}_{lt} = 0 \quad (t = 1,\ldots,NT)(b = 1,\ldots,NB)(s = 1,\ldots,NS)(ns = 1,\ldots,NNS) \tag{4}$$

$$PL^s_{lt} - (\delta_{mt} - \delta_{nt})/x_l + M(1 - z_{lt}) \geq 0 \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{5}$$

$$PL^s_{lt} - (\delta_{mt} - \delta_{nt})/x_l - M(1 - z_{lt}) \leq 0 \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{6}$$

$$PL^s_{lt} \leq PL_{l,\max} * z_{lt} \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{7}$$

$$-PL^s_{lt} \leq PL_{l,\max} * z_{lt} \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{8}$$

$$PL^{ns}_{lt} = (\delta_{mt} - \delta_{nt})/x_l \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{9}$$

$$PL^{ns}_{lt} \leq PL_{l,\max} \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{10}$$

$$-PL^{ns}_{lt} \leq PL_{l,\max} \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{11}$$

$$\delta_{mt} - \delta_{nt} \leq \delta^{\max}_{mn} + Mz_{l(t-1)} + M(1 - z_{lt}) \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL) \tag{12}$$

$$\delta_{mt} - \delta_{nt} \geq -\delta^{\max}_{mn} - Mz_{lt} - M(1 - z_{l(t-1)}) \quad (t = 1,\ldots,NT)(l = 1,\ldots,NL) \tag{13}$$

$$\sum_{l \in L_b} z_{lt} \geq 1 \quad (t = 1,\ldots,NT) \tag{14}$$

where M is a large positive number.

In (4), P_{bt} is the net injection at bus b at time t. So

$$P_{bt} = P^g_{bt} - P^d_{bt} \tag{15}$$

Here P^g_{bt} is equal to P_{it} where unit i is placed at bus b. P^d_{bt} is the value of load at bus b. The constraints for switchable lines use a single binary variable z_{lt}. When this variable is equal to one, power flow constraints on switchable lines will be the same as those of other lines. In such a case, the line will be treated the same as other lines. When the line's binary variable is zero, (5)-(6) and (7)-(8) would impose a zero flow on that line. So the line will be switched off. Constraints (12)-(13) consider the preset limits for the standing phase angle difference. The standing phase angle difference must be within its limits before an attempt is made to close breakers. Using (12)-(13), when a line is switched backed on, standing phase angle limits are imposed. Otherwise these constraints are relaxed. Using (14) the islanding is prevented. This constraint guarantees that at least one line is connected to each bus.

C. *Network Check*

Once TS feasibility check turns out to be infeasible based on the UC solution, the network check will be solved for 24 hours. Here the real power mismatch is minimized at buses while considering transmission network constraints as

$$Min \;\; v = \sum_{b=1}^{NB} (SL_{b,1} + SL_{b,2}) \tag{16}$$

S.t.

$$P_{it} = \hat{P}_{it} * \hat{I}_{it} \;\leftrightarrow\; \pi_{it} \qquad (i = 1,\ldots,NG) \tag{17}$$

$$P_{bt} - \sum_{l \in L_b} PL_{lt} + SL_{b,1} - SL_{b,2} = 0 \qquad (b = 1,\ldots,NB) \tag{18}$$

$$PL_{lt} \le PL_{l,\max} \qquad (l = 1,\ldots,NL) \tag{19}$$

$$-PL_{lt} \le PL_{l,\max} \qquad (l = 1,\ldots,NL) \tag{20}$$

$$PL_{lt} = (\delta_{mt} - \delta_{nt})/x_l \qquad (l = 1,\ldots,NL) \tag{21}$$

The solution will provide hourly cuts for the UC problem as

$$\hat{v} + \sum_{i=1}^{NG} \pi_{it}^{n} (P_{it} I_{it} - \hat{P}_{it} \hat{I}_{it}) \le 0 \tag{22}$$

Uncontrollable contingency constraints on line *l* are listed as

$$P_{bt}^{c} - \sum_{l \in L_b} PL_{lt}^{c} + SL_{b,1}^{c} - SL_{b,2}^{c} = 0 \qquad (b = 1,\ldots,NB)(c = 1,\ldots,NC) \tag{23}$$

$$PL_{lt}^{c} \le PL_{l,\max} Y_{lt}^{c} \qquad (l = 1,\ldots,NL)(c = 1,\ldots,NC) \tag{24}$$

$$-PL_{lt}^{c} \le PL_{l,\max} Y_{lt}^{c} \qquad (l = 1,\ldots,NL)(c = 1,\ldots,NC) \tag{25}$$

$$PL_{lt}^{c} - (\delta_{mt}^{c} - \delta_{nt}^{c})/x_l + M(1 - Y_{lt}^{c}) \ge 0 \qquad (l = 1,\ldots,NL)(c = 1,\ldots,NC) \tag{26}$$

$$PL_{lt}^{c} - (\delta_{mt}^{c} - \delta_{nt}^{c})/x_l - M(1 - Y_{lt}^{c}) \le 0 \qquad (l = 1,\ldots,NL)(c = 1,\ldots,NC) \tag{27}$$

Accordingly, the objective function would be changed to

$$Min \;\; v = \sum_{b=1}^{NB} (SL_{b,1} + SL_{b,2}) + \sum_{c=1}^{NC} \sum_{b=1}^{NB} (SL_{b,1}^{c} + SL_{b,2}^{c}) \tag{28}$$

In the above formulation, the state variable for line *l* contingency is zero with a zero power flow.

D. Economic Dispatch

Using the Benders decomposition, the TS subproblem is decomposed into two parts. The first part is economic dispatch problem which finds the optimal dispatch of units, given the UC schedule

$$Min \sum_{i=1}^{NG} \sum_{t=1}^{NT} [F_{ci}(P_{it}) * \hat{I}_{it}] \tag{29}$$

which is subject to unit and system constraints. The binary states of switchable lines transform this economic dispatch to a MIP problem. At the first iteration, there are no constraints on line flows or switchable line states. So, random values are assigned to these variables. But in the subsequent iterations the proper cuts from the network security check establish constraints on switchable line states. To examine the unit contingencies, (1) and (2) are considered in this problem. The contingencies that lead to infeasibility of this problem are labeled as uncontrollable and a new UC schedule will be calculated accordingly.

E. Network Security Check

The network security check is the second part of the TS subproblem which is used to check whether a converged dc power flow solution can be obtained based on economic dispatch results. So

$$Min \;\; v = \sum_{b=1}^{NB} (SL_{b,1} + SL_{b,2}) \tag{30}$$

S.t.

$$P_{it} = \hat{P}_{it} \;\leftrightarrow\; \pi_{it} \qquad (i = 1,\ldots,NG) \tag{31}$$

$$z_{lt} = \hat{z}_{lt} \;\leftrightarrow\; \mu_{lt} \qquad (l = 1,\ldots,NL) \tag{32}$$

$$P_{bt} - \sum_{l \in L_b} PL_{lt}^{s} - \sum_{l \in L_b} PL_{lt}^{ns} + SL_{b,1} - SL_{b,2} = 0 \qquad (b = 1,\ldots,NB)(s = 1,\ldots,NS)(ns = 1,\ldots,NNS) \tag{33}$$

$$PL_{lt}^{s} - (\delta_{mt} - \delta_{nt})/x_l + M(1 - z_{lt}) \ge 0 \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{34}$$

$$PL_{lt}^{s} - (\delta_{mt} - \delta_{nt})/x_l - M(1 - z_{lt}) \le 0 \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{35}$$

$$PL_{lt}^{s} \le PL_{l,\max} * z_{lt} \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{36}$$

$$-PL_{lt}^{s} \le PL_{l,\max} * z_{lt} \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{37}$$

$$PL_{lt}^{ns} = (\delta_{mt} - \delta_{nt})/x_l \qquad (l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{38}$$

$$PL_{lt}^{ns} \le PL_{l,\max} \qquad (l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{39}$$

$$-PL_{lt}^{ns} \le PL_{l,\max} \qquad (l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{40}$$

$$\delta_{mt} - \delta_{nt} \le \delta_{mn}^{\max} + Mz_{l(t-1)} + M(1 - z_{lt}) \qquad (l = 1,\ldots,NL) \tag{41}$$

$$\delta_{mt} - \delta_{nt} \ge -\delta_{mn}^{\max} - Mz_{l(t-1)} - M(1 - z_{lt}) \qquad (l = 1,\ldots,NL) \tag{42}$$

$$\sum_{l \in L_b} z_{lt} \ge 1 \qquad (t = 1,\ldots,NT) \tag{43}$$

The bus power mismatch is presented by (33). P_{bt} shows the real power injection at bus *b* at time *t* which is the bus power generation minus bus load at time *t*. Power flows as well as the state of each switchable line is obtained by (34)-(37). When a line is switched, the line flow will be set to zero and removed from power flow equations. The power flow of non-switchable lines is obtained by (38)-(40). Standing phase angle limits are considered by (41) and (42), and islanding is prevented using (43). If the total mismatch exceeds the specified limit, the cut (44) will be added to the economic dispatch for the next iteration.

$$\hat{v} + \sum_{i=1}^{NG} \pi_{it}^{n} (P_{it} - \hat{P}_{it}) + \sum_{l=1}^{NL} \mu_{lt}^{n} (z_{lt} - \hat{z}_{lt}) \le 0 \tag{44}$$

The following constraints will examine line contingencies,

$$PL_{lt}^{sc} - (\delta_{mt}^{c} - \delta_{nt}^{c})/x_l + M(1 - z_{lt}^{c}) + M(1 - Y_{lt}^{c}) \ge 0 \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{45}$$

$$PL_{lt}^{sc} - (\delta_{mt}^{c} - \delta_{nt}^{c})/x_l - M(1 - z_{lt}^{c}) - M(1 - Y_{lt}^{c}) \le 0 \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{46}$$

$$PL_{lt}^{sc} \le PL_{l,\max} z_{lt}^{c} Y_{lt}^{c} \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{47}$$

$$-PL_{lt}^{sc} \le PL_{l,\max} z_{lt}^{c} Y_{lt}^{c} \qquad (l = 1,\ldots,NL)(s = 1,\ldots,NS) \tag{48}$$

$$PL_{lt}^{nsc} = Y_{lt}^{c} (\delta_{mt}^{c} - \delta_{nt}^{c})/x_l \qquad (l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{49}$$

$$PL_{lt}^{nsc} \le PL_{l,\max} Y_{lt}^{c} \qquad (l = 1,\ldots,NL)(ns = 1,\ldots,NNS) \tag{50}$$

$$-PL_{lt}^{nsc} \le PL_{l,\max} Y_{lt}^{c} \qquad (l=1,\ldots,NL)(ns=1,\ldots,NNS)\ (51)$$

$$\delta_{mt}^{c} - \delta_{nt}^{c} \le \delta_{mn}^{\max} + Mz_{l(t-1)}^{c} + M(1-z_{lt}^{c}) \qquad (l=1,\ldots,NL)\ (52)$$

$$\delta_{mt}^{c} - \delta_{nt}^{c} \ge -\delta_{mn}^{\max} - Mz_{l(t-1)}^{c} - M(1-z_{lt}^{c}) \qquad (l=1,\ldots,NL)\ (53)$$

Constraints (45)-(48) are for switchable lines in the case of contingencies, while (49)-(51) are for non-switchable lines. If the current UC solution is infeasible for contingency c, or the maximum iteration limit is reached, this contingency will be labeled as uncontrollable and the procedure will be returned to the UC problem to find a preventive generation schedule. Using (52)-(53), the standing phase angle difference limit is considered in case of contingencies. The procedure for solving the problem is given as

Step 1. Solve the UC problem with proper cuts.

Step 2. Given the UC schedule, check the TS feasibility. If the TS problem is feasible then proceed to Step 4.

Step 3. Use the UC solution for the network check to minimize bus mismatches. Form the cuts and go to Step 1.

Step 4. Use the UC solution with proper cuts to find the optimal generation dispatch as well as the status of switchable lines. If a feasible solution is not available, label the contingency as uncontrollable and go to Step 1. Otherwise, proceed to Step 5.

Step 5. Minimize power mismatches by applying line and generation flows obtained in the economic dispatch. If the total mismatch is larger than a threshold and add the cuts to the economic dispatch for the next iteration. Similar to Step 4, check for uncontrollable contingencies and go to Step 1 if they exist. Stop the process if contingencies are controllable and the total mismatches satisfies the threshold.

III. NUMERICAL SIMULATIONS

Two case studies consisting of the six-bus system and the IEEE 118-bus system are analyzed to illustrate the performance of the proposed method. The proposed method was implemented on a 2.4-GHz personal computer using CPLEX.

A. Six-Bus System

The six-bus system is shown in Fig. 3. The objective is to calculate the least cost of dispatch with an hourly fixed load. The characteristics of generators, lines and the hourly load distribution over the 24-h horizon are given in Tables I, II and III, respectively.

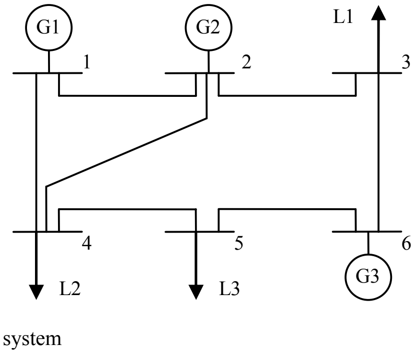

Fig. 3. Six-bus system

TABLE I
CHARACTERISTICS OF GENERATING UNITS

Unit No.		1	2	3
Bus No.		1	2	6
Cost Coefficients	c ($/MW^{2}h)	0.014	0.020	0.086
	b ($/MWh)	19.96	23	29.14
	a ($)	200	150	50
Minimum Capacity (MW)		100	10	10
Maximum Capacity (MW)		220	200	50
Startup Cost ($)		50	40	0
Shutdown Cost($)		100	200	0
Minimum Up Time (h)		4	3	1
Minimum Down Time (h)		4	2	1
Ramp Up Rate (MW/h)		40	30	20
Ramp Down Rate (MW/h)		50	35	20
MSR (MW/min)		2	1.5	0.5
QSC (MW)		15	10	10
Initial Hour		+4	+3	+1
Initial Generation (MW)		140	20	10

TABLE II
CHARACTERISTICS OF TRANSMISSION LINES

Line No.	From Bus	To Bus	X (pu)	Flow limit (MW)
1	1	2	0.170	140
2	1	4	0.258	110
3	2	3	0.037	150
4	2	4	0.197	140
5	3	6	0.018	130
6	4	5	0.037	50
7	5	6	0.140	140

TABLE III
HOURLY LOAD DEMAND

Hour	Load (MW)	Spinning Reserve (MW)	Operating Reserve (MW)
1	175.19	2.63	12.26
2	165.15	2.48	11.56
3	158.67	2.38	11.10
4	154.73	2.32	10.83
5	155.06	2.33	10.85
6	160.48	2.40	11.23
7	173.39	2.60	12.14
8	177.60	2.85	13.33
9	186.81	3.09	14.39
10	206.96	3.26	15.20
11	228.61	3.43	16.00
12	236.10	3.54	16.52
13	242.18	3.63	16.95
14	243.60	3.66	17.05
15	248.86	3.73	17.42
16	255.79	3.84	17.91
17	256.00	3.84	17.92
18	246.74	3.70	17.27
19	245.97	3.69	17.22
20	237.35	3.56	16.62
21	237.31	3.56	16.62
22	232.67	3.41	15.90
23	195.93	3.02	14.07
24	195.60	2.95	13.78

The following TS cases are considered:
Case 1: Base case UC (without contingencies)
Case 2: Outage of line 2-4 is considered in Case 1
Case 3: Outage of unit 2 is considered in Case 1

The range of standing phase angle differences that a system can withstand mostly depends on the voltage level and is usually determined by steady-state and dynamic simulations. However, we assume that the maximum standing phase angle is large enough to satisfy the associated constraints.

Case 1: UC with a dc network security check is used to find the dispatch of generating units shown in Table IV. The cheaper unit 1 is on at all hours while the more expensive unit 2 is used at peak hours to satisfy the remaining load and minimize the operating cost. Unit 2 is committed at hour 11 due to increase of load. The generation of this unit at its startup is equal to its minimum capacity. In this situation the network encounters transmission flow violation on lines 1-4 and 4-5. Therefore, expensive unit 3 should be turned on to help the system mitigate these violations. In peak hours 15-19 line 4-5 is congested, which leads to decrease in generation of unit 1 in some hours and causes increase of total operating cost. The total operating cost in this case is $125465.

The application of TS will result in the schedule in Table V. This UC schedule is obtained at the first iteration of the master problem, i.e. the first UC without considering any cuts is feasible for TS. So, the model disregards the network check in the TS master problem and proceeds to the subproblem. Imposing fewer cuts to the UC could result in a better final solution. Using TS, the total operating cost is slightly dropped to $125362. Here, at hour 11 when lines 1-4 and 4-5 are congested, lines 2-4 and 4-5 are switched off instead of turning on unit 3. With this switching, the impact of line flows on other lines is minimized since there is no loop remaining in the system. In this case all the lines can raise their flow to their flow limits as shown in Table VI. Lines 2-4 and 4-5 are switched off at hours other than peak. At peak hours 16 and 17, the security of the system cannot be satisfied with the proposed network topology. So, lines 2-4 and 4-5 are switched back on where the standing phase angle difference for the two lines are 10.24 and 1.85 degrees, respectively.

Case 2: In this case the outage of line 2-4 is considered. Using the dc network security check, the UC in Case 1 cannot satisfy the system security. The newly obtained UC is shown in Table VII with highlighted states that are different than those in Case 1. Unit 2 is committed at hours 10 and 24 to mitigate flow violations and satisfy the security. Line 1-2 is congested at hours 12-22. The total operating cost is $125848. However, the UC solution given in Case 1 will not require any changes when we utilize TS. The unit schedule is the same as that shown in Table V. Line schedule is shown in Table VIII with highlighted changes in comparison with the base case. Line 4-5 is in service at peak hours 16 and 17 and off otherwise. The standing phase angle of line 4-5 at hour 16 is 0.3 degrees. Therefore, the line 2-4 contingency is handled with corrective TS. This corrective action is performed at the network security check of the TS subproblem. Also congestions are reduced where line 1-2 is only congested at peak hours 16 and 17. The new operating cost is $125470 which shows a 0.3% improvement.

Case 3: When considering the outage of unit 2, unit 1 will not be able to satisfy the hourly load. Therefore unit 3 is committed at some hours. In this case, the preventive schedule shown in Table IX is obtained with a more expensive daily operating cost of $126413. However, by utilizing the proposed TS approach, a feasible UC schedule is found which leads to an infeasible solution for the contingency of unit 2. When the contingency of unit 2 is considered as an uncontrollable contingency, a new UC schedule is achieved and shown in Table X. Comparing this table with Table IX, unit 3 is not committed at hour 10 with TS. The flow violations at this hour are mitigated by the switching of lines 2-4 and 4-5. Table XI shows the schedule of lines in the preventive solution and Table XII shows the schedule of lines after the outage of unit 2. The improved operating cost in this case is $126271.

TABLE IV
UC SCHEDULE OF SIX-BUS SYSTEM IN CASE 1

Unit	Hours (0-24)
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
2	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0
3	0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0

TABLE V
UC SCHEDULE OF SIX -BUS SYSTEM IN CASE 1 USING TS

Unit	Hours (0-24)
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
2	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0
3	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

TABLE VI
LINE SCHEDULE OF SIX -BUS SYSTEM IN CASE 1 USING TS

Line	Hours (0-24)
2-4	- 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
4-5	- 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0

TABLE VII
UC SCHEDULE OF SIX -BUS SYSTEM IN CASE 2

Unit	Hours (0-24)
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
2	0 0 0 0 0 0 0 0 0 0 **1** 1 1 1 1 1 1 1 1 1 1 1 1 1 **1**
3	0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0

TABLE VIII
LINE SCHEDULE OF SIX -BUS SYSTEM IN CASE 2 USING TS

Line	Hours (0-24)
2-4	- 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4-5	- **0 0 0 0 0 0** 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0

TABLE IX
UC SCHEDULE OF SIX -BUS SYSTEM IN CASE 3 USING DC NETWORK SECURITY CHECK

Unit	Hours (0-24)
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
2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0

TABLE X
UC SCHEDULE OF SIX -BUS SYSTEM IN CASE 3 USING TS

Unit	Hours (0-24)
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
2	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0

TABLE XI
LINE SCHEDULE OF SIX -BUS SYSTEM IN CASE 3 USING TS BEFORE OUTAGE OF UNIT 2

Line	Hours (0-24)
2-4	- 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 0 1
4-5	- 0 0 0 0 0 0 0 0 0 1 0 1 1 0 1 1 1 1 1 1 1 1 0 0

TABLE XII
LINE SCHEDULE OF SIX -BUS SYSTEM IN CASE 3 USING TS AFTER OUTAGE OF UNIT 2

Line	Hours (0-24)
2-4	- 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4-5	- 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

In these three studied cases, all lines are considered as switchable. However, only lines 2-4 and 4-5 are switched in these cases. Considering Fig. 3, by switching each one of lines 2-3, 3-6, 4-5 and 5-6, loop 2-3-4-5-6-2 will be relaxed. So, switching each one of them is a good choice. Since line 4-5 has the lowest capacity among the others, and thus more probable to congest, it can be the best choice for switching. This simple conclusion is consistent with the obtained results. By switching of line 4-5, the flow of other lines in its loop, i.e. lines 2-3, 3-6 and 5-6, are independent from the power flow in the system. In the other words, these lines can raise their flows to the maximum limits independent of the flow of other lines. After switching of line 4-5, one of lines in the other loop of the system can be a good choice for switching, i.e. lines 1-2, 1-4 and 2-4. Since unit 1 is the most economical and also the largest unit in the system, it is not wise to switch the lines connected to it. So, line 2-4 is the best choice for this loop. With switching of both lines 2-4 and 4-5, there are still enough lines connected to bus 4 to satisfy its load. It can be simply concluded here that by considering lines 2-4 and 4-5 as switchable lines in the system, loops can be relaxed while meeting the load balance requirements. Performing this simple analysis, just these two lines can be considered as switchable instead of all lines. This assumption helps to find better optimal solution in less time.

B. *IEEE 118-Bus System*

A modified IEEE 118-bus system is used to study the SCUC with TS. The system has 118 buses, 54 units and 186 branches. The data for this system is found in motor.ece.iit.edu/data/ SCUC_118test.xls. Two cases are considered. The first case is the base case UC and the second one is SCUC when considering contingencies. In the TS feasibility check part the *Presolve* function of CPLEX is used. *Presolve* can indicate execution error problems, like circumstance that the problem is infeasible or unbounded [19].

Case 1: In this case at first the SCUC approach is used to find the optimal generation schedule of units shown in Table XIII. This result is achieved after 5 iterations between the UC master problem and the subproblem with a total operating cost of $1081320.36. Using TS, seven lines are considered as switchable. The UC schedule found in the first iteration of the problem cannot satisfy the TS feasibility and proper cuts are added to the UC master problem. The feasible schedule is found after 2 iterations and shown in Table XIV with bold values representing the changes. Most of UC changes occur close to peak hours when more congestion is probable. The TS schedule is shown in Table XV with a total operating cost of $1068371.83 which signifies a 1.20% improvement in the total operating cost as compared with the UC solution. The total execution time is 94s.

Case 2: In this case, three simultaneous contingencies are considered in the system. The contingencies include outages of unit 13, line 75-77 and line 85-89. Using the SCUC approach, the UC schedule shown in Table XVI is obtained. The total operating cost is $1081898. To apply the proposed approach, the same lines as in Case 1 are considered switchable. The first UC result is feasible for the outage of line 75-77. So, the contingency of line 75-77 is controllable. Since the UC solution cannot lead to a feasible solution for the outages of unit 13 and line 85-89, these contingencies are uncontrollable. The new UC solution considering the two uncontrollable contingencies leads to a feasible solution regarding all three contingencies. The switchable line schedule is shown in Tables XVII and XVIII, where Table XVII shows the schedule in base case and Table XVIII shows the schedule after considering contingencies. The corresponding UC solution is shown in Table XIX with a total operating cost of $1080846, which shows a 0.06% improvement.

TABLE XIII
UC SCHEDULE OF IEEE 118 -BUS SYSTEM

Unit	Hours (0-24)
1	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
2-3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0
4-5	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
6	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
7	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
8	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
9	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0
10-11	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
12-13	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0
14	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
15	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
16	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
17	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 0 0 1 0 0
18	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 1 0 0
19	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
20-21	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
22-23	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
24-25	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
26	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0
27-29	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
30	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
31	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0
32	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0
33	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
34-35	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
36	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
37	0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
38	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
39	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
40	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
41	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
42	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
43	0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
44-45	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
46	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
47	0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0
48	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0
49-50	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
51	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0 0 0
52	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
53	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
54	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0

IV. CONCLUSIONS

The application of TS is considered in solving SCUC. An efficient preventive-corrective action scheme was used to deal with contingencies. The features of the proposed TS approach can be listed as follow.

- This model can be used for congestion management.

Changing the network topology would lead to changes in line flows and consequently changes congestion levels.

- The number of switchable lines was limited here. This assumption is consistent with practical switching applications. If we increase the number of switchable lines, it is possible to find better solutions but the problem will converge more slowly.
- Since the proposed method uses the Benders decomposition in both SCUC and TS, it is convenient to use the method for large power systems. The decomposition makes the TS problem suitable for handling a large set of contingencies.

Additional points for improving the method:

- Proper methods for identifying the optimal set of switchable lines will be considered. Such methods could include system operation strategies. For example in the IEEE 118-bus system, line 164 is a good choice for switching since it is switched off in the entire scheduling period.
- Practical line switching strategies will be considered like how often a line can be switched off or how long it needs to be on/off.

TABLE XIV
UC SCHEDULE OF IEEE 118 -BUS SYSTEM WITH TS

Unit	Hours (0-24)
1	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
2-3	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
4-5	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
6	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 **0** 0 0 0 0 0 0 0
7	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
8	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 **1** 0 0 0 0 0 0 0
9	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 **1** 0 **0** 0 0 0 0 0
10-11	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
12-13	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 **0** **0** 1 0 0 0 0 0 0 0
14	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 **0**
15	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 **0** 1 0 0 0 0 0 0 0
16	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 **0** 0
17	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 **0** 0 0 **0** 0 0
18	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 **0** 0 0
19	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 **0** 0
20-21	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
22-23	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
24-25	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
26	0 0 0 0 0 0 0 0 0 0 **1** 1 1 1 1 1 1 1 1 1 1 1 1 0 0
27-29	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
30	0 0 0 0 0 0 0 0 0 0 **0** **0** 1 1 1 1 1 1 1 1 1 1 1 **0** 0
31	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 **0** **0** 1 0 0 0 0 0 0 0
32	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 **0** 1 **1** 0 0 0 0 0 0 0
33	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
34	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
35	0 0 0 0 0 0 0 0 0 **1** 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
36	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
37	0 0 0 0 0 0 0 0 0 **0** 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
38	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
39	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
40	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
41	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
42	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
43	0 0 0 0 0 0 0 0 **0** 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
44-45	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
46	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
47	0 0 0 0 0 0 0 0 0 0 0 0 **0** 1 1 1 1 1 1 1 1 **1** **1** 0 0
48	0 0 0 0 0 0 0 0 0 0 0 **0** 1 1 1 1 1 1 1 1 **0** **0** **0** 0 0
49-50	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
51	0 0 0 0 0 0 0 0 0 0 0 **0** **0** 1 1 1 1 1 1 1 1 **1** **1** 0 0
52	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
53	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 **0** 0
54	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 **1** 0 0 0 0 0 0

- The switching status of lines is employed in economic dispatch by means of cuts. If we use additional constraints to make stronger connections between the status of switchable lines and the generation dispatch, these binary variables will be adjusted more accurately, which helps the problem find the optimal solution in less iteration. An example of such a connection can be found in [20].

TABLE XV
TRANSMISSION LINE SCHEDULE OF IEEE 118 -BUS SYSTEM USING TS

Line	Hours (0-24)
30	- 1 1 0 0 0 1 1 0 0 0 0 1 0 1 0 0 0 0 0 1 1 0 1 1
78	- 0 1 0 0 0 1 1 0 0 0 0 1 1 0 0 0 0 0 0 1 1 0 1 1
90	- 1 1 0 0 0 1 1 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 1 1
115	- 0 1 1 1 1 1 1 0 0 1 0 1 0 1 1 0 1 0 0 1 1 1 1 1
151	- 1 1 1 1 1 1 1 0 0 0 1 1 0 0 1 1 1 1 1 0 0 1 1 1
159	- 1 0 0 0 0 0 1 1 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1
164	- 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

TABLE XVI
UC SCHEDULE OF IEEE 118 -BUS SYSTEM CONSIDERING CONTINGENCIES

Unit	Hours (0-24)
1-3	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
4-5	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
6	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
7	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
8	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
9	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0
10-11	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
12-13	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
14	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
15	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
16	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
17-18	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
19	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
20-21	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
22-23	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
24-25	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
26	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
27-29	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
30	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0
31	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0
32	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
33	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
34-35	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
36	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
37	0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
38	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
39	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
40	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
41-42	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
43	0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
44-45	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
46	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
47-48	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
49-50	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
51-52	0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 0 0
53	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
54	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0

TABLE XVII
LINE SCHEDULE OF IEEE 118 -BUS SYSTEM BEFORE CONTINGENCIES

Line	Hours (0-24)
30	- 1 0 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1
78	- 0 0 0 0 0 0 0 0 0 0 1 1 0 1 0 1 1 0 0 0 1 0 0 0
90	- 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
115	- 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
151	- 1 1 1 1 1 0 1 1 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0 1
159	- 1 1 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
164	- 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

TABLE XVIII
LINE SCHEDULE OF IEEE 118 -BUS SYSTEM AFTER CONTINGENCIES

Line	Hours (0-24)
30	- 0 1 1 0 0 0 0 1 1 0 0 1 1 0 1 1 0 1 0 1 0 1 0 0
78	- 1 0 0 0 0 1 1 0 1 1 1 1 1 1 1 1 0 1 1 0 1 1 1 1
90	- 1 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1
115	- 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
151	- 1 1 1 1 1 0 1 1 0 0 1 0 0 1 0 0 1 0 1 0 0 1 0 1
159	- 0 1 1 0 0 0 1 0 0 0 0 1 0 1 1 0 0 1 0 1 1 1 0 1
164	- 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

TABLE XIX
UC SCHEDULE OF IEEE 118 -BUS SYSTEM USING TS AND CONTINGENCIES

Unit	Hours (0-24)
1-2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
4-5	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
6	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
7	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
8	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0
9	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0
10-11	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
12	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0
13	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 0 0 0 0 0
14	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
15	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0
16	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
17	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
18	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
19	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
20-21	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
22	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
23	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
24-25	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
26	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0
27-29	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
30	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0
31	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0
32	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0
33	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
34-35	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
36	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
37	0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
38	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
39	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
40	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
41-42	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
43	0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
44-45	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
46	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
47	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 0
48	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0
49	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
50	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
51	0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0
52	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0
53	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
54	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0

REFERENCES

[1] M. Shahidehpour, H. Yamin, and Z. Y. Li, *Market Operations in Electric Power Systems*. New York: Wiley, 2002.

[2] A.J. Conejo, E. Castillo, R. Mínguez, and R. García-Bertrand, *Decomposition Techniques in Mathematical Programming*, Springer, 2006.

[3] R. Bacher and H. Glavitsch, "Network topology optimization with security constraints," *IEEE Trans. Power Syst.*, vol. 1, pp. 103-111, Nov. 1986.

[4] G. Schnyder and H. Glavitsch, "Integrated security control using an optimal power flow and switching concepts," *IEEE Trans. Power Syst.*, vol. 3, pp. 782-790, May 1988.

[5] G. Schnyder and H. Glavitsch, "Security enhancement using an optimal switching power flow," *IEEE Trans. Power Syst.*, vol. 5, pp. 674-681, May 1990.

[6] J. G. Rolim and L. J. B. Machado, "A study of the use of corrective switching in transmission systems," *IEEE Trans. Power Syst*., vol. 14, pp. 336-341, Feb. 1999.

[7] W. Shao and V. Vittal, "Corrective switching algorithm for relieving overloads and voltage violations," *IEEE Trans. Power Syst*., vol. 20, no. 4, pp. 1877-1885, Nov. 2005.

[8] G. Granelli, M. Montagna, F. Zanellini, P. Bresesti, R. Vailati and M. Innorta, "Optimal network reconfiguration for congestion management by deterministic and genetic algorithms," *Electr. Power Syst. Res.,* vol. 76, pp. 549-556, Apr. 2006.

[9] E. B. Fisher, R. P. O'Neill, and M. C. Ferris, "Optimal transmission switching," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1364-1355, Aug. 2008.

[10] K. W. Hedman, R. P. O'Neill, E. B. Fisher, S. S. Oren, "Optimal transmission switching – sensitivity analysis and extensions," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1469-1479, Aug. 2008.

[11] N. Deeb and M. Shahidehpour, "A decomposition approach for minimizing real power losses in power systems," *Proc. Inst. Elect. Eng.*, vol. 138, no. 1, pp. 27–38, Jan. 1991.

[12] N. Deeb and M. Shahidehpour, "Cross decomposition for multi-area optimal reactive power planning," *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 1539–1544, Nov. 1993.

[13] M. Shahidehpour and V. Ramesh, "Nonlinear programming algorithms and decomposition strategies for OPF," in *IEEE/PES Tutorial on Optimal Power Flow*. Piscataway, NJ: IEEE Press, 1996.

[14] H. Ma and M. Shahidehpour, "Transmission constrained unit commitment based on benders decomposition," *Elect. Power Energy Syst.*, vol. 20, no. 4, pp. 287–294, Apr. 1998.

[15] A. M. Geoffrion, "Generalized benders decomposition," *J. Optim Theory Appl.*, vol. 10, no. 4, pp. 237–261, 1972.

[16] M. Adibi and R. Kafka, "Power system restoration issues," *IEEE Comput. Appl. Power*, vol. 4, no.2, pp. 19-24, Apr. 1991.

[17] A. Ketabi and A. Ranjbar, "New approach to standing phase angle reduction for power system restoration," *IEEE Elect. Power Eng.*, PowerTech Budapest, 1999.

[18] N. Martins, E. J. Oliviera, W. C. Moreira, J. L. R. Pereira and R. M. Fontoura, "Redispatch to reduce rotor shaft impacts upon transmission loop closure," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 592–600, May. 2008.

[19] The GAMS Development Corporation Website, 2006. [Online]. Available: http://www.gams.com/.

[20] J. Guo and Z. Li, "Network reduction with unknown transmission line status," *39th North American Power Symp.*, 2007.