

Multiobjective Congestion Management and Transmission Switching Ensuring System Reliability

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Abstract—Congestion in transmission lines is an important topic in power systems and it continues to be an area of active research. Various approaches have been proposed to mitigate congestion especially immediate ready ones such as Congestion Management (CM) and Transmission Switching (TS). Using either of the two or their combination (CMTS) may have undesirable consequences like increasing operational costs or increasing the number of switching of transmission lines. More switching aggravates system reliability and imposes extra costs on the operator. In this paper, a multi-objective model is introduced which reduces overall operation costs, the number of switching in transmission lines, and the congestion of lines, compared to available approaches which employ congestion management and TS simultaneously. To verify the performance of the proposed model, it is implemented using GAMS and tested on 6- and 118- bus IEEE test systems. A benders' decomposition approach was employed.

Keywords—component, multi-objective model, congestion management, transmission switching, benders' decomposition.

I. NOMENCLATURE

A. Indices and sets

t	Time
$(.)^s$	Scenario
$(.)^l$	Loss
J, r, m	Elements of a piecewise linearized model of radiation loss
g, b, k	Index of generators, buses, and lines, respectively
l	Number of piecewise linear blocks

B. Variables and Constants

R_g^+, SR_g^+	Maximum ramp up/ramp down rate [MW]
q_s	Solar radiation heat losses [MW/m]
P_g^{\max}, P_g^{\min}	Active power limitation for generators [MW]
Q_g^{\max}, Q_g^{\min}	Reactive power limitation for generators [MW]
P_k^{\max}, Q_k^{\min}	Active/reactive power limitation for lines [MW]
$\Delta V^{\max}, \Delta V^{\min}$	Voltage limitation for busses [p.u]
$\delta_k^{\max}, \delta_k^{\min}$	Angle difference limitation for lines
M	A large positive
I_{base}	Base current [A]
$SU_{g,t}, SD_{g,t}$	Start-up and shut-down cost for generators
α	Solar radiation coefficient
$Q_{se}, Q_{s,k,t}$	Solar radiation [MW/m ²]
$a_{k,j,t}, b_{k,j,t}$	Piecewise linearized radiation loss ratios

dt	Time changes [h]
mCp	Heat capacity [J/(m·°C)]
$T_{k,t}^\alpha$	Ambient temperature [°C]
zc_k^s, uc_g^s	Contingency state of (unit g)/(line k)
ajj, cij	Failure probability of CB linearized coefficient
qc	Convection heat losses [MW/m]
qr	Radiation heat losses [MW/m]
$ql_{k,t}^l$	Ohmic losses [MW/m]
dT_c	Line temperature changes [°C]
$Tr_{k,j,t}$	Piecewise linearized temperature [Ω]
$ur_{k,j,t}$	Binary variable for radiation losses
$T_{k,t}^s$	Line temperature [°C]
P_D	Real power of load
P_g^{\max}, P_g^{\min}	Active power limitation for generators [MW]
Q_g^{\max}, Q_g^{\min}	Reactive power limitation for generators [MW]
P_k^{\max}, Q_k^{\min}	Active/reactive power limit for lines [MW]
$\Delta V^{\max}, \Delta V^{\min}$	Voltage change limitation for buses [p.u]
$\delta_k^{\max}, \delta_k^{\min}$	Angle difference limitation for lines
$M, VOLL$	Large positive numbers
zc_k^s, uc_g^s	Contingency state of (unit g)/(line k)

II. INTRODUCTION

Transmission Switching (TS) is one of the methods investigated by researchers to reduce costs in Security Constrained Unit Commitment (SCUC).

In [1], TS is employed to better handle contingencies and in [2] it is used to find N-1 secure states. In [3], a SCUC model with TS is used while considering wind power plants. Another use of TS is congestion management, leading to economic benefits. In [4], congestion management reduces the costs. A real-time congestion management system for distribution systems is proposed in [5]. The majority of recent studies, like [5], aim to reduce the power changes of generators to manage contingencies in lines. Predictably, utilizing congestion management results in higher cost in most of the cases. In this paper a TS power flow is used to manage congestion in lines, in a manner such that satisfies reduction of congestion in lines and reduction of operational costs simultaneously. Note that scheduling too much switching for lines reduces the functional lifespan of Circuit Breakers (CBs).

Ref. [6] presents an equation which obtains EENS based on failure probability of CBs, since failure or switching of load-side CBs will lead to interrupted load.

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In [6], a multi-objective function is proposed which optimizes the number of switching for lines. With fewer switching in lines, failure probability of CB will be reduced, so the overall reliability of the system will be improved. Another approach which leads to operational cost reduction in power systems is to involve dynamic line rating (DLR) in SCUC problems. Generally, load shedding and other methods which use DLR are studied in power systems to reduce the spinning reserve [7]. In [8], heat balance equation (HBE) has been studied, but the lines' power flow is not considered. In [9], a DC model is proposed for optimal power flow (OPF). To describe system behavior more accurately, in [10], an AC model is presented for OPF. A piecewise linear AC power flow is presented in [11]. In [12], a linear AC power flow considering linear losses is proposed. In [13], a linearized formulation of AC multi-period transmission expansion planning is proposed.

The main prospects of this paper are summarized as follows:

- A congestion management model with TS is proposed to reduce line congestion and operation costs.
- A linear presentation of the proposed congestion management model is introduced.
- A multi-objective model is suggested to decrease the number of switching in lines.

III. PROPOSED CMTS MODEL

While the use of TS increases flexibility, overusing CBs decreases their lifespan and imposes repair and maintenance costs on the operator. So it would be beneficial to introduce a model which aims to reduce the costs and the number of switching at the same time. In previous literature, TS is employed as a useful tool for congestion management. Reference [4] uses the sensitivity factor of power changes when a contingency occurs to handle the line congestions.

Equations of the SCUC problem with TS are introduced here:

$$\min \sum_{g=1}^N Cp(p_g^0 + p_g^s) + C_L \quad (1)$$

$$p_g^{\min} u \leq p_g \leq p_g^{\max} u \quad (2)$$

$$\Delta p_g^s = p_g^0 - p_g^s \quad (3)$$

$$p_g^{\min} - p_g^0 \leq \Delta p_g^s \leq p_g^{\max} - p_g^0 \quad (4)$$

$$p_k^s - M(1 - Z_k) \leq p_k^s \leq p_k^s + M(1 - Z_k) \quad (5)$$

$$-p_k^{\max} Z_k \leq p_k^s \leq p_k^{\max} Z_k \quad (6)$$

$$\sum_{g=1}^N p_g^s - \sum_{k=1}^N p_k^s = p_D - p_{sh}^s \quad (7)$$

Equation (1) minimizes the operation costs. Equation (2) restricts the maximum and minimum power of generators. Power change of generators and their limitation are presented in (3) and (4). Equations (5) and (6) enable the TS operation. Power balance is formulated in equation (7). The following equations are related to congestion management:

$$\sum_{g=1}^N (GS_g^k \Delta p_g) + p_k^0 = p_k^s \quad (8)$$

$$\sum_{g=1}^N \Delta p_g = 0 \quad (9)$$

$$GS_g^k = \frac{\Delta p_k}{\Delta p_g} \quad (10)$$

Equation (8) is the line flow, based on the changes in generator powers when a contingency occurs. Generally, generator powers should change in a way that causes no violations in line power flows. Equation (9) is the sum of all power changes in the generators. Equation (10) is the sensitivity factor of generators respective to the lines and is fully discussed in [4]. The problem here is that if a line is committed to be out ($Z_k=0$), P_k would become zero as well in (8). In this case, Δp should be valued in a way that sets (4) to zero. To eliminate this problem, the following equation is proposed:

$$\sum_{g=1}^N GS_g^k \Delta p_g Z_k + p_k^0 Z_k = p_k^s \quad (11)$$

In this equation, when a line is out, it is no longer responsible for setting the equation to zero. Equation (11) is nonlinear. A linear representation is introduced here:

$$\sum_{k=1}^L \underbrace{GS_g^k \Delta p_g Z_k}_{\Delta p_k} + p_k^0 Z_k = p_k^s \quad (12)$$

$$\sum_{k=1}^L \Delta p_k + p_k^0 Z_k = p_k^s \quad (13)$$

$$Z_k = 1 \xrightarrow{\text{constraint (8)}} \Delta p_k = \sum_{g=1}^N GS_g^k \Delta p_g \quad (14)$$

$$Z_k = 0 \xrightarrow{\text{constraint (8)}} \Delta p_k = 0 \quad (15)$$

$$\sum_{g=1}^N GS_g^k \Delta p_g - (1 - Z_k)M \leq \Delta p_k \quad (16)$$

$$\sum_{g=1}^N GS_g^k \Delta p_g + (1 - Z_k)M \geq \Delta p_k \quad (17)$$

$$-Z_k M \leq \Delta p_k \quad (18)$$

$$Z_k M \geq \Delta p_k \quad (19)$$

In (12) and (13), Δp_k is the change in transmitting power of lines due to changes in power of the generators and binary variable Z_k . As shown in (14) and (15), if a line is switched on, the power changes of that line is non-zero and is defined by the power changes of the generators. And if a line is switched off, the power changes of that line will be zero and that directly influences the power changes of the generators and the operation costs accordingly. This part is defined with equations (16) to (19). As mentioned before, the high number of switching in lines is harmful and increases the maintenance costs. In the majority of recent studies of TS, the high number of switching in lines is neglected.

The number of switching directly influences the longevity of CB and decreases it. To improve the reliability of the system, another objective function is added, to co-optimize the number of switching in lines. To do so, the summation of binary variables of switching between the periods is minimized as it is defined in (20).

$$\min \sum_k \sum_t Z_{k,t} - Z_{k,t-1} \quad (20)$$

Subjected to (21) and constraints (2) to (7) and (16) to (19):

$$\min \sum_{g=1}^N Cp(\Delta p) \quad (21)$$

Now there are two objectives, one that minimizes the operation costs and the other minimizes the number of switching in lines. To solve this problem, a multi-objective method is used. As it is described in [14], our multi-objective problem can be transformed into a single objective problem by using a weighting factor. The proposed model is summarized below:

$$\min \sum_{g=1}^N Cp(\Delta p) + X \sum_k \sum_t Z_{k,t} - Z_{k,t-1} \quad (22)$$

This objective function is subjected to equations 2 to 7 and equations 16 to 19 as constraints. In (22), the first summation sums up the operation costs and the second summation is the number of switching in all lines and over the time horizon. To diminish the number of switching the second summation should be minimized. A weighting factor is multiplied in the second summation, as the units of cost and the number of switching are different. In [15], a weighting factor is introduced for multi-objective functions. Here, X is the weighting factor.

IV. PROPOSED MODEL FOR SCUC

The objective function of the problem is defined in (32) which minimizes the generation cost and minimizes the number of switching. In this problem, generation costs including active/reactive power and reserve are assumed to be available. Constraints (32)-(37) are associated with active and reactive generated power constraints, Start-up/shut-down constraints and Ramp up/down constraints in which, uc_g^s is the contingency state of unit g, and $u_{g,t}$ is generating unit entry/exit binary variable [16]. For each scenario, $\Delta r_{g,t}^s$ determines the reserve capacity of each generator. Constraints on entry and exit of generators, ramp up/down constraints, and constraints on reserve capacity of each generator are shown in (38-40), respectively. Equation (41) presents reactive power balance constraints.

Inequalities (42-45) represent the way that TS operates for active and reactive powers. zc_k^s is contingency state of line k. $z_{k,t}$ is the binary variable of entry and exit of lines. M is a sufficiently large positive number. $P_{b,m,k,t}^s$ shows power flowing between buses b and m. If the line is in, $z_{k,t}$ will be 1 and lines' power flow is $P_{b,m,k,t}^s$. If the decision is that the line should be switched off, $z_{k,t}$ will be zero and lines' power flow would be between a large positive and negative number. Constraints (42-45) are related to lines' power flow limitations.

In this power flow, bus voltage changes amplitude and bus voltage angle limitations are also considered and defined as (46) - (47). Heat balance constraints in line are addressed in (48-52). In this equation, time is divided into one-hour intervals and wind speed is supposed to be low. Constraints (53-56) are related to the presented model.

$$\min \sum_{g=1}^N Cp(\Delta p) + X \sum_k \sum_t Z_{k,t} - Z_{k,t-1} \quad (32)$$

$$P_g^{min} u_{g,t} uc_g^s \leq P_{g,t} + \Delta r_{g,t}^s \leq P_g^{max} u_{g,t} uc_g^s \quad (33)$$

$$Q_g^{min} u_{g,t} uc_g^s \leq Q_{g,t}^s \leq Q_g^{max} u_{g,t} uc_g^s \quad (34)$$

$$v_{g,t} - w_{g,t} = u_{g,t} - u_{g,t-1} \quad (35)$$

$$\sum_{t'=t-UT_g+1}^t v_{g,t'} \leq u_{g,t}, \quad \forall g, t \in \{UT_g, \dots, T\} \quad (36)$$

$$\sum_{t'=t-DT_g+1}^t w_{g,t'} \leq 1 - u_{g,t}, \quad \forall g, t \in \{DT_g, \dots, T\} \quad (37)$$

$$P_{g,t} - P_{g,t-1} \leq R_g^+ u_{g,t-1} + R_g^{SU} v_{g,t} \quad (38)$$

$$P_{g,t-1} - P_{g,t} \leq R_g^+ u_{g,t} + R_g^{SU} w_{g,t} \quad (39)$$

$$-SR_g^+ \leq \Delta r_{g,t}^s \leq SR_g^+ \quad (40)$$

$$\sum_{\forall g(b)} (P_{g,t} + \Delta r_{g,t}^s) - \sum_{\forall k(b,m)} (P_{k,t}^s + 0.5PL_{k,t}^s) = PD_{b,t}^s - P_{sh,b,t}^s \quad (41)$$

$$\sum_{\forall g(b)} Q_{g,t}^s + \sum_{\forall k(b,m)} (Q_{k,t}^s - 0.5QL_{k,t}^s) = QD_{b,t} \quad (42)$$

$$P_{b,m,k,t}^s - M(1 - z_{k,t} zc_k^s) \leq P_{k,t}^s \leq P_{b,m,k,t}^s + M(1 - z_{k,t} zc_k^s) \quad (43)$$

$$Q_{b,m,k,t}^s - M(1 - z_{k,t} zc_k^s) \leq Q_{k,t}^s \leq Q_{b,m,k,t}^s + M(1 - z_{k,t} zc_k^s) \quad (44)$$

$$-P_k^{max} z_{k,t} zc_k^s \leq P_{k,t}^s \leq P_k^{max} z_{k,t} zc_k^s \quad (45)$$

$$-Q_k^{max} z_{k,t} zc_k^s \leq Q_{k,t}^s \leq Q_k^{max} z_{k,t} zc_k^s \quad (46)$$

$$\delta_k^{min} \leq \delta_{k,t}^s \leq \delta_k^{max} \quad (47)$$

$$\Delta V^{min} \leq \Delta V_{b,t}^s \leq \Delta V^{max} \quad (48)$$

$$mC_{pk}(T_{k,t+1}^s - T_{k,t}^s) = \Delta_t \begin{pmatrix} ql_{k,t}^s(T_{k,t}^s) + qs_{k,t}^s \\ -qc_{k,t}^s(T_{k,t}^s) - qr_{k,t}^s(T_{k,t}^s) \end{pmatrix} \quad (49)$$

$$T_{k,t}^s \leq T_{max} \quad (50)$$

$$qs_{k,t} = Ks_{k,t} D_k Qs_{k,t} \quad (51)$$

$$qr_{k,t}^s(T_{k,t}^s) = K_r^r \sum_j (a_{k,j,t} Tr_{k,j,t}^s + ur_{k,j,t} b_{k,j,t}) \quad (52)$$

$$qc_{k,t}^s(T_{k,t}^s) = \left[1.01 + 0.0372 \left(\frac{Dp_j V_w}{\mu_j} \right)^{0.52} \right] kf K_{angle} (T_{k,t}^s - T_{k,t}^a) \quad (53)$$

$$\sum_{g=1}^N GS_g^k \Delta p_g - (1 - Z_k) M \leq \Delta p_k \quad (54)$$

$$\sum_{g=1}^N GS_g^k \Delta p_g + (1 - Z_k) M \geq \Delta p_k \quad (55)$$

$$-Z_k M \leq \Delta p_k \quad (56)$$

$$Z_k M \geq \Delta p_k \quad (57)$$

Master Problem: In this level, constraints on UC including ramp up/down, minimum uptime, minimum downtime, and power balance constraints are considered. The problem objective function is to minimize generating power costs.

$$\min \sum_{g=1}^N Cp(\Delta p) + X \sum_k \sum_t Z_{k,t} - Z_{k,t-1} \quad (58)$$

$$\sum_g P_{g,t} = PD_{b,t} \quad (59)$$

$$\text{(Using equations 33-56 with consideration of } S=0) \quad (60)$$

Sub-problem 1, System security evaluation: Sub-problem 1, contains system security constraints with no contingency. The system security constraints are: lines' power flow, generator's power considering reserve power, reserve power, transmission switching, transmission lines, voltage angles in busses and bus voltages. The objective function of the sub-problem 1 minimizes the slack variables.

$$\min \sum_b (SP_{1,b,t} + SP_{2,b,t}) + \sum_n (SQ_{1,b,t} + SQ_{2,b,t}) \quad (61)$$

(Using equations 33-56 with consideration of $S=1$) (62)

$$P_{g,t} = \hat{P}_{g,t} \rightarrow \gamma_{g,t} \quad (63)$$

$$u_{g,t} = \hat{u}_{g,t} \rightarrow \eta_{g,t} \quad (64)$$

$$z_{k,t} = \hat{z}_{k,t} \rightarrow \mu_{k,t} \quad (65)$$

$$Q_{g,t} = \hat{Q}_{g,t} \rightarrow \lambda_{g,t} \quad (66)$$

In order to use the Bandar-e-Cut, instead of the network variables ($P_{g,t}, u_{g,t}, \dots$), they must define their dual variables, which are here, $\lambda_{g,t}$, $\eta_{g,t}$ and $\gamma_{g,t}$ are dual variables that are defined for (63)-(66). The Benders' cut, that is obtained from sub problem, can be written as follows:

$$(SP_{1,b,t} + SP_{2,b,t}) + \sum_n (SQ_{1,b,t} + SQ_{2,b,t}) + \sum_k \mu_{k,t} (z_{k,t} - \hat{z}_{k,t}) + \sum_g [\gamma_{g,t} (P_{g,t} - \hat{P}_{g,t}) + \eta_{g,t} (u_{g,t} - \hat{u}_{g,t}) + \lambda_{g,t} (Q_{g,t} - \hat{Q}_{g,t})] \leq 0 \quad (67)$$

The flowchart of the proposed model is presented in Fig. 1.

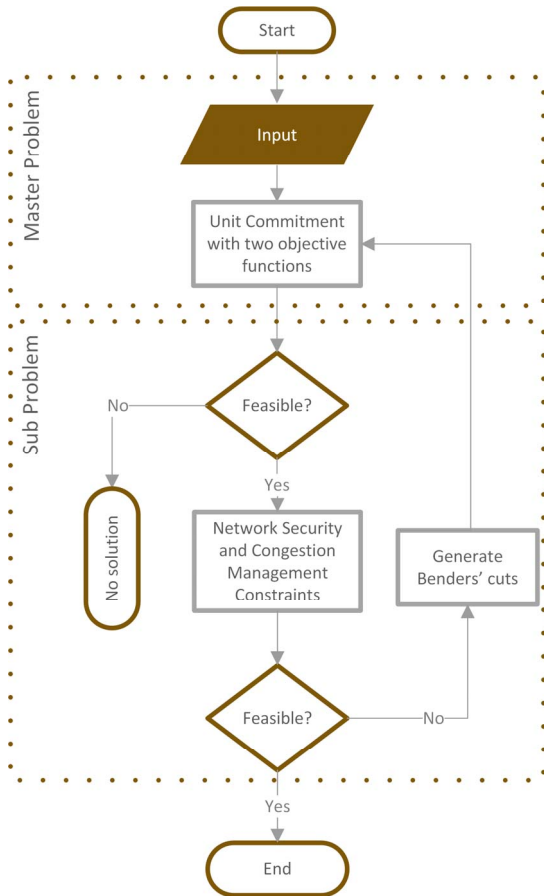


Fig. 1. The flowchart of the proposed model.

V. CASE STUDY AND RESULTS

In this section, the proposed model was tested on both the IEEE 6- and 118-bus test systems and the results were provided for a 24-hour period. The proposed model is also compared with a SCUC model in different contingencies which does not consider the reliability of CBs. GAMS software is used for the simulations.

In most cases congestion management is employed in real-time market. However, to discern the effects of the proposed model, obtained results for a 24-hour period are presented here for a 6-bus and a 118-bus system. Table I contains the results of the regular CMTS model and the proposed CMTS model for the 6-bus and 118-bus systems. The switching schedules of different cases that are mentioned in table I are shown in Fig. 2 and Fig. 3 for 6-bus and 118-bus systems, respectively. As the purpose is to minimize operation costs, the operator will use the cheapest generators to supply the demanded load when the system is operating with no failure. But as a contingency occurs (e.g. generator number 2 goes out), the power shortage will be compensated from the remaining generators and to avoid congestion in lines, congestion management strategies are employed. As expected from the proposed CMTS model, Δk and Δp are switched in a way that the overall costs are reduced compared with the regular model. Figures 4 and 5 depict the power changes of remaining generators for proposed and regular CMTS model.

For example, in the regular CMTS model in hour 22, the output power of the first generator is reduced by 0.019 PU and at the same hour the output power of the third generator is increased which is expensive and leads to a growth in the operation costs. But in the proposed CMTS model and at the same hour, the required power is supplied by the first generator itself. The overall operation cost is decreased from 6953.344 for the regular CMTS model to 6812.000 for the proposed CMTS model. This cost reduction is of course more noticeable in bigger systems.

TABLE I. COMPARING TS OPERATION IN REGULAR CMTS AND PROPOSED CMTS MODEL WITH DIFFERENT SCENARIOS

		Case #	Line	Number of switching	Cost (\$)
6 bus system (generator 2 is out)	Regular CMTS	I	2-4	7	3.108×10^5
		II	4-5	9	
	Proposed CMTS	III	2-4	2	2.3935×10^5
		IV	4-5	4	
118-bus system (generator 13 is out)	Regular CMTS	V	30	10	1.091×10^6
		VI	78	12	
		VII	90	8	
	Proposed CMTS	VIII	30	6	1.0075×10^6
		IX	78	5	
		X	90	4	

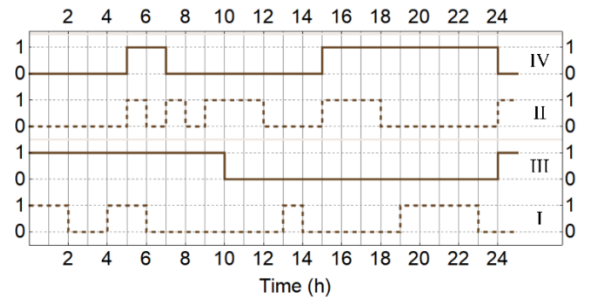


Fig. 2. Switching schedule in 6-bus system.

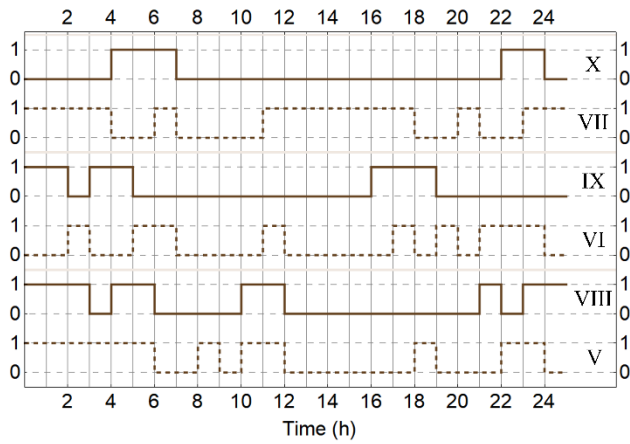


Fig. 3. Switching schedule of some lines in 118-bus system.

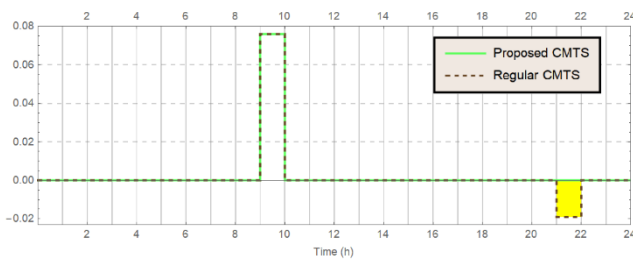


Fig. 4. Power changes of generator number 1 (6-bus system).

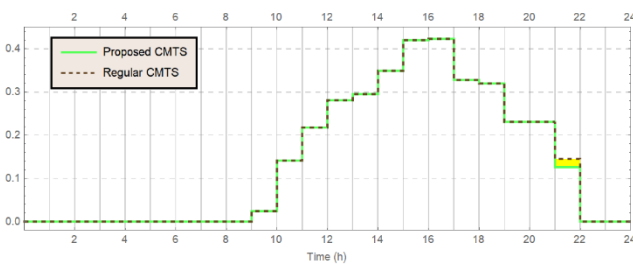


Fig. 5. Power changes of generator number 3 (6-bus system).

For the 118-bus system the overall costs are reduced from 1.09149×10^6 for the regular CMTS model to 1.00275×10^6 for the proposed CMTS model. The proposed model also tries to reduce the number of switching in lines, alongside with reducing the operation cost and congestion of lines. As results show, in the regular CMTS the number of switching of lines 2-4 and 4-5 are 7 and 9 respectively which are dropped to 2 and 4 for the proposed model.

As mentioned before, the proposed model decreases both costs and the number of switching in lines. So, line congestions will be handled with fewer switching in lines which will lessen the failure probability of CBs and improve the reliability of CBs, thus the overall costs will be reduced accordingly. The number of switching in lines is also dropped in 118-bus system simulation and the obtained results are provided in Table III. Results for the 118-bus system confirm that the initial purposes of decreasing both operation costs and the number of switching in lines are fulfilled.

VI. CONCLUSION

In SCUC problems, power system security is of great importance. Security requirements should be attained in a cost-wise manner. Transmission switching and congestion management are tools that reinforce system security, but in some cases, they are not preferable economically. Also, the high number of switching in lines leads to higher operation costs and decreases the system reliability in the long term. In this paper a multi-objective CMTS model was presented which reduces the congestion of lines and overall operation costs with fewer switching in lines. The improvements brought by the proposed model were evident in the results. The proposed model was simulated on 6-bus and 118-bus test systems with GAMS software.

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