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Author(s): Sheikh, Morteza; Aghaei, Jamshid; Letafat, Armin; Rajabdorri, Mohammad; Niknam, Taher; Shafie-Khah, Miadreza; Catalão, João P. S.

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Security-Constrained Unit Commitment Problem With Transmission Switching Reliability and Dynamic Thermal Line Rating

Morteza Sheikh, Jamshid Aghaei, *Senior Member, IEEE*, Armin Letafat, Mohammad Rajabdorri, Taher Niknam, Miadreza Shafie-Khah, *Senior Member, IEEE*, and João P. S. Catalão, *Senior Member, IEEE*

***Abstract*—In security-constrained unit commitment (SCUC) problems, one approach to decrease operation costs is using a transmission switching (TS) tool. In SCUC problems with TS, one of the main challenges is that there is no limitation for the number of switching of circuit breakers (CB) in the system. In this article, the reliability of CB is merged into the SCUC problem with the TS and is considered as a limiting factor for switching. With a more reliable CB, the overall reliability of the system will be increased. So, it can be concluded that the reliability of a CB affects the amount of load shedding. Reliability of a CB is a nonlinear equation based on the number of switching in a period. An approach is presented to linearize the switch reliability equation. In this article, the power flow model uses an improved linear ac optimal power flow and a dynamic thermal line rating (DTLR) model, which considers the weather conditions. Other than CB reliability, DTLR in SCUC problems affects the number of switching and, as a result, operation costs will be significantly decreased. The proposed model is empowered by Bender's decomposition and is tested on 6-bus and 118-bus IEEE test systems.**

***Index Terms*—Benders' decomposition, dynamic thermal line rating (DTLR), expected energy not supplied (EENS), linear ac power flow, transmission switching (TS).**

NOMENCLATURE

A. Indices and sets

t	Time periods.
$(.)^s$	Scenario.
$(.)^v$	Number of Benders' iteration.
$(.)^c$	Set of 1 to v-1.
$(.)^l$	Loss.
g, b,k	Index of generators, buses and lines, respectively.
l	Number of piecewise linear blocks.
f, r	Elements of piecewise linearized model of radiation loss.
j	Dummy set for time periods.

B. Variables

q_c	Convection heat losses [MW/m].
q_r	Radiation heat losses [MW/m].
$ql_{k,t}$	Heat losses due to lines' power flow [MW/m].
dT_c	Line temperature changes [°C].
$R(T_C)$	Thermal resistance[Ω/m].
$Tr_{k,f,t}$	Piecewise linearized temperature of radiation losses [°C].
$ur_{k,f,t}$	Binary variables for the linearized equation of radiation losses.
${T^s}_{k,t}$	Line temperature [°C].
Z^{up}	Upper bound optimal solution of the original problem.
Z^{down}	Objective function.
$P^s_{k,t}, Q^s_{k,t}$	Line active/reactive power flows [p.u.].
$PL^s_{k,t}, QL^s_{k,t}$	Line active/reactive power losses [p.u.].
$P_{sh_{b,t}}$	Amount of load shedding due to CB failure [p.u.].
$Pj_{k,j}, Pc_{k,j}$	Part of load shedding due to CB failure as a function of a binary variable [p.u.].
${P^0}_{g,t}, Q^0_{g,t}$	Generator active/reactive power [p.u.].
$\Delta r^s_{g,t}$	Generator reserve power [p.u.].
${z^s}_{k,t}, {u^s}_{g,t}$	Binary variable for ON/OFF status of lines and units, respectively.
${v^s}_{g,t}, {w^s}_{g,t}$	Start-up/shutdown binary variable for units.
$\Delta V^s_{b,t}, V_b$	Voltage changes and voltage of each bus [p.u.].
$\Delta\delta_k(l)$	Phase angle difference of blocks.
$\delta^s_{k,t}$	Phase angle difference across transmission line *k*.

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M. Sheikh, J. Aghaei, M. Rajabdorri, and T. Niknam are with the Shiraz University of Technology, Shiraz 71557-13876, Iran (e-mail: mortezash23@gmail.com; aghaei@sutech.ac.ir; mohammadrajabdorri23@gmail.com; niknam@sutech.ac.ir).

A. Letafat is with Islamic Azad University, Kazeroun 7319866451, Iran (e-mail: arminletafat23@gmail.com).

M. Shafie-Khah is with the School of Technology and Innovations, University of Vaasa, 65200 Vaasa, Finland (e-mail: miadreza@gmail.com).

J. P. S. Catalão is with the Faculty of Engineering, Institute for Systems and Computer Engineering, Technology and Science, University of Porto, Porto 4200-465, Portugal (e-mail: catalao@ubi.pt).

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δ_k^+, δ_k^-	Nonnegative variables used to replace $\delta_{k,t}^s$.
$SP^s{}_{1,b,t}, SP^s{}_{2,b,t}$	Slack variables of active power [p.u.].
$SQ^s{}_{1,b,t}, SQ^s{}_{2,b,t}$	Slack variables of reactive power [p.u.].
$f(t)$	Failure rate.
dl	Probability of CB failure.
$\lambda^s{}_{g,t}, \mu^s{}_{k,t}$ $\gamma^s{}_{g,t}, \eta^s{}_{g,t}$	Dual variables.
$h(l)$	Slope of the *l*th piecewise linear section for loss modeling.
N_k	Number of switching in line k.
RL	Reliability of CB.
EENS	Expected energy not supplied.
$bj_{k,j}$	Binary variables for linearizing dl.

C. Constants

R^{S+}_g, SR_g^+	Maximum ramp up/ramp down rate [p.u.].
qs	Solar radiation heat losses [MW/m].
$P_g^{\max}, P_g^{\min}$	Active power limitation for generators [p.u.].
$Q_g^{\max}, Q_g^{\min}$	Reactive power limitation for generators [p.u.].
$PD_{b,t}^s$	Bus demands [p.u.].
$P_K^{\max}, Q_K^{\max}$	Active/reactive power limit for lines [p.u.].
$\Delta V^{\max}, \Delta V^{\min}$	Voltage change limitation for buses [p.u.].
$SU_{g,t}, SD_{g,t}$	Start-up and shut-down cost for generators [\$].
$\delta_k^{\max}, \delta_k^{\min}$	Max/min of angle difference across line *k*.
M, VOLL	Large positive numbers (depends on the system under study).
$\delta m^{\max}$	Limit of piecewise linear blocks.
I_{base}	Base current [A].
K_f, K_{angle}	Coefficients of hot weather and wind speed.
α	Solar radiation coefficient.
$K_{k,t}^S$	Coefficients of solar radiation.
D	Conductor diameter [mm].
$a_{k,f,t}, b_{k,f,t}$	Coefficients of piecewise linearized radiation loss ratios.
H_C	Altitude of the sun [°].
Z_C	Sun angle [°].
Z_1	Line angle [°].
dt	Time changes [h].
ρ_f	Air density [kg/m^3].
V_w	Wind speed [m/s].
μ_f	Air dynamic viscosity [Pa·s].
mC_p	Heat capacity [J/(m·°C)].
$R_{k,\text{ref}}$	Conductor resistance at temperature $T_{k,\text{ref}}$ [Ω].
T_a	Ambient temperature [°C].
$T_{k,\text{ref}}$	Line reference temperature [°C].
$K_{k,t}^r$	Radiation losses coefficients.
ε	Weather emissivity.
n_1	Number of switching which is occurred before *t*.
ε_1	Low positive value for convergence.
P	Value of $f(t)$ for $N = 23$.
zc_k^s, uc_g^s	Contingency state of (line *k*)/(unit *g*).
$Tr_{k,f,t}^{\min}, Tr_{k,f,t}^{\max}$	Lower/upper bounds of conductor temperature for piecewise linearization of radiation heat loss [°C].
$T_{\max}$	Line maximum temperature [°C].
Cj_j, lj_j	Coefficients for linearizing failure probability of CB at *j*.
τ	Time horizon.
UT_g, DT_g	Minimum down time and minimum up time for unit *g*.

I. Introduction

A. Motivation and Aims

ONE way to increase the system security is using transmission switching (TS) in security-constrained unit commitment (SCUC) problems. TS can provide flexible control processes for the voltage instability, contingency management, and system security.

Despite these advantages, one main problem of TS is the high number of switching in a specific period. More switching reduces the CB's lifetime, which makes the system less reliable and, as a result, the operation and maintenance costs in a period will rise. Since any changes in the reliability of a device highly influence the overall reliability of the system, the purpose here is to develop a limitation in the number of switching, by considering the switch reliability. By involving switch reliability in the SCUC problem, the problem formulation becomes nonlinear. Having nonlinear equations complicates the problem and the optimum solution will be harder to reach. Accordingly, a linear model is proposed to linearize the problem. TS operates in such a way that in addition to curbing the number of switching, it increases the reliability. Also, to improve the TS operation in the SCUC model, dynamic thermal line rating (DTLR) is added as a security constraint to consider weather conditions in the ac power flow formulations. That lessens the line heat losses and operating costs.

B. Literature Review

To reduce the operation costs and to increase the system reliability in SCUC problems, different approaches have been proposed. One of them is using TS as a security constraint in power systems. This approach, by considering the switching of transmission lines, finds an optimum power flow for units under the system constraints.

In [1], TS is used to reduce contingency effects. In [2], TS is implemented to treat $n-1$ security criteria and in [3], it is employed to improve the power flow and to cope with overvoltage. In [4] and [5], an SCUC model with TS is proposed that include wind power.

TS is utilized in [6] to mitigate the uncertainty of wind power generation. The work in [7] indicates that using TS in wind farm integrated power systems can relieve transmission bottlenecks and reduce expansion and operation costs. The growing share of fluctuating and less predictable renewable generations questions the overall reliability of the system [8]. Reliability of a device reflects the system behavior. For devices like power circuit breakers (CB), switching is the main feature of the device [9].

In [10], the data related to CBs reliability are presented. The reliability of a CB includes different parts, such as operation mechanism, control, and insulation. It is assumed that if a CB in the load side does not operate for any reason, load would not be supplied. The importance of CB reliability and its major role in power system is noted in [11]. In [12], an equation is proposed that relates the expected energy not supplied (EENS) to the probability of CB failure. Another approach that leads to operation cost reduction in power systems involves dynamic line rating (DLR) in SCUC problems. Generally, in the system operation, load shedding and other methods using DLR are used to reduce spinning reserve [13].

In [14], a heat balance equation (HBE) has been studied without considering lines' power flow. To also include lines' power flow, in [15], a dc model is proposed for the optimal power flow (OPF) with TS, and since dc models lack the accuracy to model the system behavior, in [16], an ac model is presented for OPF. Even though these approaches are accurate, they are not favorable because of their computational burden. A piecewise linear ac power flow is presented in [17].

In [18], a linear ac power flow considering linear losses is proposed. In [19], a linearized formulation of the ac multiperiod transmission expansion planning is proposed.

C. Features and Capabilities

To the best of authors' knowledge, the main features and capabilities of this article with respect to the previous works in the area can be mentioned as follows.

1) Proposing an SCUC model with TS considering CBs' reliability and developing a limitation for the number of switching to reach higher reliability.
2) Proposing a linear approximation to linearize CBs' reliability equation.
3) Involving DTLR in SCUC to improve the accuracy of estimating thermal losses.

In previous studies containing the uses of TS, the number of switching is not restricted in any way. This issue has a major impact on system reliability and operation cost. In this article, this matter has been considered to increase the reliability and to reduce operation costs. The remaining sections of this article are organized as follows. Section II refers to the modeling of CBs reliability to be later used in the SCUC formulation considering DTLR. In Section III, DTLR equations are proposed. In Section IV, SCUC formulation is fully discussed and CB reliability is involved. Simulation results are reported in Section V and conclusions are drawn in Section VI.

II. Modeling of CB Reliability

A. Failure Function of CBs

Close (ON) or open (OFF) state of a CB depends on its operating mechanism and control, and plays a major role in the breaker reliability [20]. The CB behavior can be divided into three main parts: insulation, control systems, and operation mechanism. Insulation part includes main insulations for grounding and separating units from the system. The second part is its control system that includes contactors, relays, heaters, thermostats, fuses, etc. The operation mechanism has also different parts, such as mechanical transmission and energy storage [10]. One parameter that influences the reliability of the CB is the number of switching in a specific period. By more switching, CB failure will be more probable and that deteriorates the reliability of the system. To determine the reliability of CBs, it is needed to calculate the probability of the CB failure. In this case, the first step is to measure the CB failure based on the number of switching in each period. Medjoudj and Aissana [21] proposed a reliability analysis of the CB subjected to random shocks. Random shocks are used for failure modeling in different references and for various components of power system [22]–[24].

$$f\left(t\right) = 0.002N^2 + 40.43N. \tag{1}$$

If we consider a *t* hour period, *N* is the number of switching, which has occurred in period *t* summed up with the number of switching which has happened in prior periods. To be more clear, *N* is the accumulation of the two different parts. The former is the variable number of switching in period *t*. The latter is the sum of all switching before *t* and is a constant. It is assumed that when a CB reaches its most expected (maximum) number of switching, it would not operate anymore. $f(t)$ is an experimental measure and has no units or dimensions.

This function is then divided by the highest value that $f(t)$ can get (P) to give us a probability for the CB failure.

$$dl = \frac{0.002N^2 + 40.43N}{P}. \tag{2}$$

In (2), the numerator represents CB failure based on the number of switching *N* and the denominator is the CB failure, $f(t)$, when *N* has reached to its maximum. It means that *P* is the maximum value that $f(t)$ can take (i.e., when CB is in its worst condition) and CB will fail to operate after that. dl is the probability of the CB failure in a *t*-hour period. Since with higher (lower) probability of the CB failure, the reliability of the CB decreases (increases), the following equation is claimed:

$$\mathrm{RL} = 1 - dl \tag{3}$$

where RL represents the reliability of CB. One purpose of this article is to improve the reliability of CB and the system by alleviating the number of switching. This aim will be met when dl is closest to zero.

B. Effect of CBs Reliability on Load Shedding Cost

In SCUC with TS, CBs are considered for each line and the CB failure leads to transmission line outage. Therefore, it is concluded that the high probability of CB failure results in the transmission line outages. More switching in CBs increases the probability of failure and that increases the probability of transmission line outage. On the other hand, the line outage can affect the power balance equation and load shedding. The portion of EENS that is caused by the CB failure can be determined based on the CB reliability as

$$\mathrm{EENS} = \sum_{b} \sum_{t} dl \ P_{sh_{b,t}} \tag{4}$$

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where $P_{sh_{b,t}}$ is the amount of load shedding due to the CB failure and EENS is the amount of energy not supplied because of the CB failure. Evidently, (2) and (4) are nonlinear functions and should be linearized. In [25], based on scenario probability, a linear approximation for EENS is presented. So, it should be rewritten as a function of binary variables

$$N_k = \sum_t |z_{k,t} - z_{k,t-1}| + n_1 \tag{5}$$

$$N_k = \sum_j bj_{k,j} lj_j \quad + n_1 \tag{6}$$

$$dl = \frac{1}{P} \begin{bmatrix} \sum_k \sum_j 0.002 bj_{k,j} Cj_j + 2\sum_j bj_{k,j}\ lj_j \ \ n_1 0.002 \ + n^2{}_1 \\ + \sum_k \sum_j 40.43\ lj_j\ bj_{k,j} + 40.43 n_1 \end{bmatrix}. \tag{7}$$

In (5), $z_{k,t}$ is the binary variable that indicates whether a line is in or out. $z_{k,t} - z_{k,t-1}$ for all periods is equal to the total number of switching that is scheduled for line *k*. The number of switching of a line in a time period can be obtained by this function. Also, n_1 is the number of switching that occurred before *t*. According to (6), number of lj_j points is equal to the number of switching in period *t*, based on these obtained points and by using (7). lj_j is the set of numbers from 0 to 23. Maximum possible number of switching for a line in a 24-h horizon is 23. N_k is the number of switching and is determined in (5). Then, in (6), binary variable $bj_{k,j}$ takes values to keep the equality. For example, suppose that $N_k = 3$. In this case, there are only two possibilities to preserve the equality, either $bj_{k,1}$ and $bj_{k,2}$ will be 1 and others will be zero, or $bj_{k,3}$ will be 1 and others will be zero. In (7), lj_j and Cj_j are constant in each *j* point and $bj_{k,j}$ is a binary variable. By using (7) in (2), (8) can be achieved. In (8), $Cj_j = {lj_j}^2$. In this case, EENS can be calculated based on the failure probability of the CB (dl) as

$$\begin{aligned} \text{EENS} = \frac{1}{P} \Bigg(& \sum_b \sum_t \sum_k \sum_j \Big(0.002\ \underbrace{bj_{k,j}\ Cj_j\ P_{sh_{b,t}}}_{Pc_{k,j}}\Big) \\ & + \sum_b \sum_t \sum_k \sum_j \Bigg(0.004\ n_1\ \underbrace{bj_{k,j}\ lj_j\ \ P_{sh_{b,t}}}_{Pj_{k,j}} \Bigg) \\ & + \sum_b \sum_t \sum_k \sum_j (40.43\ \underbrace{bj_{k,j}\ lj_j\ \ P_{sh_{b,t}})}_{Pj_{k,j}} \\ & + \sum_b \sum_t \left(\left(n^2{}_1 + 40.43\ n_1 \right) P_{sh_{b,t}} \right). \end{aligned} \tag{8}$$

Equation (8) is composed of the product of binary variable $bj_{k,j}$ and variable associated with load shedding $P_{sh_{b,t}}$. This multiplication causes nonlinearity in the equation. In (8), two variables ($P_{sh_{b,t}}$ which is related to load shedding and $bj_{k,j}$ which is binary) are multiplied and that makes this equation nonlinear. Equation (8) can be linearized as follows:

$$\begin{aligned} \text{EENS} = \frac{1}{P} \Bigg(& \sum_k \sum_j 0.002 Pc_{k,j} \\ & + \sum_k \sum_j (40.43 + 0.004 n_1) Pj_{k,j} \\ & + \sum_b \sum_t \left(n^2{}_1 + 40.43 n_1 \right) P_{sh_{b,t}} \Bigg) \end{aligned} \tag{9}$$

$$(5) - (6) \tag{10}$$

$$-\, bj_{k,j} M \le Pc_{k,j} \le bj_{k,j} M \tag{11}$$

$$\begin{aligned} & P_{sh_{b,t}} Cj_j - \ (1 - bj_{k,j}) M \le Pc_{k,j} \\ & \le P_{sh_{b,t}} Cj_j + (1 - bj_{k,j}) M \end{aligned} \tag{12}$$

$$-\, bj_{k,j} M \le Pj_{k,j} \le bj_{k,j} M \tag{13}$$

$$\begin{aligned} & P_{sh_{b,t}} lj_j - \ (1 - bj_{k,j}) M \ \le Pj_{k,j} \\ & \quad \le P_{sh_{b,t}} + \ (1 - bj_{k,j}) M. \end{aligned} \tag{14}$$

In (9), $Pj_{k,j}$ and $Pc_{k,j}$ are the parts of load shedding, caused by line outage. $Pj_{k,j}$ is the multiplication of $bj_{k,j}$, $P_{sh_{b,t}}$, and lj_j. $Pc_{k,j}$ is the multiplication of $bj_{k,j}$, $P_{sh_{b,t}}$, and Cj_j.

As (8) states, if $bj_{k,j} = 1$, then $Pc_{k,j} = P_{sh_{b,t}} Cj_j$, and $Pj_{k,j} = P_{sh_{b,t}} lj_j$. Else if $bj_{k,j} = 0$, $Pj_{k,j}$ and $Pc_{k,j}$ will be zero. So linearized version of (8) should lead to the same results. To linearize the first part of (8), constraints (11) and (12) can be used. In case that $bj_{k,j} = 0$, $Pc_{k,j} = 0$ in (11) and in (12), since *M* is a large positive number, then $Pc_{k,j} = M$. As the aim is to minimize the load shedding, $Pc_{k,j} = 0$ will be chosen here. On the contrary, when $bj_{k,j} = 1$, then $Pc_{k,j} = M$ in (11) and $Pc_{k,j} = P_{sh_{b,t}} Cj_j$ in (12). As the purpose is minimizing load shedding, $Pc_{k,j} = P_{sh_{b,t}} Cj_j$ is chosen in this case. The second part of (8) can similarly be linearized by using (13) and (14). In case that $bj_{k,j} = 1$, $Pj_{k,j} = P_{sh_{b,t}} lj_j$ and when $bj_{k,j} = 0$, $Pj_{k,j} = 0$. Generally, EENS and EENS costs are calculated based on the failure probability of CB.

$$C_r = \text{VOLL} \times \text{EENS}\ . \tag{15}$$

In (15), C_r is the EENS cost and VOLL is a large positive number. Since each CB has its repair and maintenance cost, this cost should add up to the operation costs.

$$C_l = dl \times\ C_e. \tag{16}$$

In (16), C_e is the cost of repair and maintenance of CB. In this case, when the number of switching is reduced, dl and C_l will be diminished accordingly, and ultimately the operation cost will be decreased.

III. Dynamic Thermal Line Rating

The HBE of lines contains different terms which include [26]: first, heat losses due to lines' power flow (q_l); second, heat losses due to solar radiation (qs); third, radiation losses

(qr); and fourth, convection losses (qc). Accordingly, based on temperature changes in conductor HBE is defined as

$$qc + qr + mC_p \frac{dT_c}{dt} = qs + I^2 R(T_c) \tag{17}$$

$$qr = 1.0178\, D\varepsilon \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \tag{18}$$

$$qr_{k,t}\left(T_{k,t}\right) = Kr_{k,t} \sum_f \left(a_{k,f,t} Tr_{k,f,t} + ur_{k,f,t} b_{k,f,t}\right) \tag{19}$$

$$\sum_f ur_{k,f,t} = 1 \tag{20}$$

$$ur_{k,f,t} Tr_{k,f,t}^{\min} \le Tr_{k,f,t} \le ur_{k,f,t} Tr_{k,f,t}^{\max} \tag{21}$$

$$\sum_f Tr_{k,f,t} = T_{k,t}. \tag{22}$$

Equation (18) presents the radiation losses as a nonlinear function of ambient temperature and conductor temperature. In [12], a piecewise linear approximation is presented for qr. According to Suwanasri *et al.* [9], $T - qr$ diagram can be divided into linear parts, i.e., as shown in (19)–(22). In this method, the conductor temperature is the sum of the temperature of each part. qc is a function of weather conditions, such as wind speed, conductor diameter, ambient temperature, conductor temperature, and angle of wind crossing the conductor (K_{angle}). Based on the IEEE standard [26], the following equations are defined for the low and high wind speeds, respectively:

$$qc_1 = \left[1.01 + 0.0372 \left(\frac{D \rho_f V_w}{\mu_f} \right)^{0.52} \right] K_f\, K_{\text{angle}} \left(T_c - T_a\right) \tag{23}$$

$$qc_2 = \left[1.0119 \left(\frac{D \rho_f V_w}{\mu_f} \right)^{0.6} K_f K_{\text{angle}} \left(T_c - T_a\right) \right]. \tag{24}$$

Usually, the angle of wind crossing the conducting wires is assumed to be perpendicular and it can be assumed that K_{angle} coefficient is equal to 1. Based on that, convection losses equation will be linear. Heat losses due to lines' power flow (q_l) in terms of lines' thermal resistance are obtained as

$$ql_{k,t}\left(T_{k,t}\right) = R\left(T_{k,t}\right) \left|I_{k,t}\right|^2 \quad I_{\text{base}}^2. \tag{25}$$

Ohmic losses are shown with a nonlinear nonconvex equation. According to Henneaux and Kirschen [5], by assuming that thermal resistance is in its worst condition (maximum temperature), the equation will be as follows:

$$R_{k,t}\left(T_{k,t}\right) = R_{k,\text{ref}} \left(1 + \alpha_k \left(T_{k,t} - T_{k,\text{ref}}\right)\right) \tag{26}$$

$$ql_{k,t}\left(T_{k,t}\right) \ge R_{k,t}\left(T_{\max}\right) \left(\left|Q_{k,t}\right|^2 + \left|P_{k,t}\right|^2 \right) I_{\text{base}}^2. \tag{27}$$

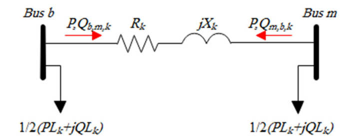

Fig. 1. Transmission line model considering losses.

IV. Linearized Full SCUC Model

A. Linear AC Power Flow Considering Losses

In [18], as it is shown in Fig. 1, line losses are considered as loads in buses and lines' power flow is defined as follows:

$$P_k = V_b^2 gb_k - V_b V_m \left(gb_k \cos\delta_k + bg_k \sin\delta_k\right) \tag{28}$$

$$Q_k = -V_b^2 \left(bg_k + bg_{k0}\right) + V_b V_m \left(bg_k \cos\delta_k + gb_k \sin\delta_k\right). \tag{29}$$

Since (28) and (29) are nonlinear, with the following approximations, they can be linearized:

$$\cos\delta_k \approx 1 \tag{30}$$

$$\sin\delta_k \approx \delta_k. \tag{31}$$

As it is known, phase differences between buses are very small, and based on that, trigonometric parts can be eliminated. Furthermore, voltage magnitude in buses is near to 1 per unit (p.u.) with small changes

$$V_b = 1 + \Delta V_b. \tag{32}$$

Based on these approximations, lines' power flow equations will become linear and can be calculated as follows:

$$P_k \approx \left(1 + 2\Delta V_b\right) gb_k - \left(1 + \Delta V_b + \Delta V_m\right) \left(gb_k + bg_k \delta_k\right) \tag{33}$$

$$\begin{aligned} Q_k \approx &- \left(1 + 2\Delta V_b\right) \left(bg_k + bg_{k0}\right) \\ &+ \left(1 + \Delta V_b + \Delta V_m\right) \left(bg_k - gb_k \delta_k\right) \end{aligned} \tag{34}$$

$$P_{b,m,k} = \left(\Delta V_b - \Delta V_m\right) gb_k - bg_k \delta_k \tag{35}$$

$$Q_{b,m,k} = -\left(1 + 2\Delta V_b\right) bg_{k0} - \left(\Delta V_b - \Delta V_m\right) bg_k - gb_k \delta_k. \tag{36}$$

Here, $Q_{b,m,k}$ and $P_{b,m,k}$ are the simplified forms from (33) and (34). Since in this model, line losses are modeled as loads in buses, in [15], line loss equations are suggested as follows:

$$PL_k = gb_k \delta_k^2 \tag{37}$$

$$QL_k = bg_k \delta_k^2. \tag{38}$$

It is noted that δ_k^2 in (37) and (38) is a nonlinear term. In [6], a piecewise linear approach is used to linearize the losses.

$$\delta_k = \delta_k^+ - \delta_k^- \tag{39}$$

$$\sum_{l=1}^{L} \Delta\delta_k(l) = \left|\delta_k\right| = \delta_k^+ - \delta_k^- \tag{40}$$

$$0 \le \Delta\delta_k(l) \le \frac{\delta m^{\max}}{L} \tag{41}$$

$$0 \leq \Delta\delta_k\left(l\right) \leq \Delta\delta_k(l-1) \tag{42}$$

$$k\left(l\right) = \left(2l-1\right)\frac{\delta m^{\max}}{L} \tag{43}$$

$$\delta_k^2 = \sum_{l=1}^{L} k\left(l\right)\Delta\delta_k\left(l\right). \tag{44}$$

Here, k and l are associated with lines and piecewise linearization of each line, respectively. L is the total number of the linearized pieces. gb_k and bg_k are the characteristics of lines and are completely discussed in [6]. According to (39)–(44), line losses in (37) and (38) can be piecewise linearized as follows:

$$PL_k = gb_k\sum_{l=1}^{L} h\left(l\right)h\delta_k\left(l\right) \tag{45}$$

$$QL_k = -bg_k\sum_{l=1}^{L} h\left(l\right)h\delta_k\left(l\right). \tag{46}$$

B. Proposed Model for SCUC

In this article, an SCUC model using TS, considering CB reliability as a constraint to limit the number of switching, is proposed. The objective function of the problem is defined in (47), which minimizes the generation cost (C) and the load shedding cost. In this problem, generation costs including active/reactive power and reserve are assumed to be available. The power production cost is assumed to be linear and the cost function of each generator is from [6]. Equation (47) also include the costs of starting-up and shutting-down of the units. These costs are multiplied by binary variables for startup/shutdown of the generating units, so their costs will add up when a unit starts up or shuts down. The costs of maintenances of the CBs and the costs of load shedding are shown by C_r and C_l in (15) and (16). Constraints (48) and (49) are associated with active and reactive generated power constraints, in which, uc_g^s is the contingency state of unit g. Constraint (50) indicates the binary logic of binary variables. Constraints (51) and (52) indicate the minimum up and minimum down time of the units. Ramp up/down constraints are shown in (53) and (54) [4]. 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 (55). Equation (56) is active power balance considering line losses and load shedding. In this equation, other than the normal conditions, contingency conditions are also included. In normal conditions, $\Delta r_{g,t}^s$ is zero. When a contingency occurs, ${P^0}_{g,t}$ would not change, but $\Delta r_{g,t}^s$ will take values to balance power. Equation (57) presents reactive power balance constraints. Inequalities (58) and (59) represent the way that TS operates for active and reactive powers. zc_k^s is contingency state of line k. ${z^s}_{k,t}$ is the binary variable of entry and exit of lines. M is a large positive number. $P_{b,m,k,t}^s$ shows power flowing between buses b and m. If the line is in, ${z^s}_{k,t}$ 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, ${z^s}_{k,t}$ will be zero and lines' power flow would be between a large positive and negative number. Constraints (60) and (61) are related to lines' power flow limitations. Line losses are included for this power flow and constraints on active and reactive powers are presented in (62)–(65). In this power flow, bus voltage changes amplitude and bus voltage angle limitations are also considered and defined as (66)–(70). From (17) to (23), (26), (27), (71), and (72) are associated with DTLR. As mentioned earlier, the line temperature is variable, but should not exceed its maximum and this limitation is shown in (71). In fact, ql relates the heat balance with the model.

$$\min Z^{\text{down}} = \sum_t\sum_g \times \begin{bmatrix} C\left({P^0}_{g,t}\right) + SU_{g,t}({v^s}_{g,t}) \\ +SD_{g,t}({w^s}_{g,t}) + C\Delta r_{g,t}^s + C_r + C_l \end{bmatrix} \tag{47}$$

$$P_g^{\min}{u^s}_{g,t}uc_g^s \leq {P^0}_{g,t} + \Delta r_{g,t}^s \leq P_g^{\max}{u^s}_{g,t}uc_g^s \tag{48}$$

$$Q_g^{\min}{u^s}_{g,t}uc_g^s \leq Q_{g,t}^s \leq Q_g^{\max}{u^s}_{g,t}uc_g^s \tag{49}$$

$${v^s}_{g,t} - {w^s}_{g,t} = {u^s}_{g,t} - {u^s}_{g,t-1} \tag{50}$$

$$\sum_{t'=t-UT_g+1}^{t} {v^S}_{g,t'} \leq {u^S}_{g,t} \quad \forall g, t \in \{UT_g, \ldots, \tau\} \tag{51}$$

$$\sum_{t'=t-DT_g+1}^{t} {w^s}_{g,t'} \leq 1 - {u^s}_{g,t} \quad \forall g, t \in \{DT_g, \ldots, \tau\} \tag{52}$$

$${P^0}_{g,t} - {P^0}_{g,t-1} \leq {R^{s+}}_g{u^s}_{g,t-1} + R_g^{SUs}{v^s}_{g,t} \tag{53}$$

$${P^0}_{g,t-1} - {P^0}_{g,t} \leq {R^{s+}}_g u_{g,t}^s + R_g^{SUs}{w^s}_{g,t} \tag{54}$$

$$-\mathrm{SR}_g^+ \leq \Delta r_{g,t}^s \leq \mathrm{SR}_g^+ \tag{55}$$

$$\sum_{\forall g(b)}\left({P^0}_{g,t} + \Delta r_{g,t}^s\right) - \sum_{\forall k(b,m)}\left(P_{k,t}^s + 0.5PL_{k,t}^s\right) = PD_{b,t}^s - {P^s}_{sh_{b,t}} \tag{56}$$

$$\sum_{\forall g(b)} Q_{g,t}^s + \sum_{\forall k(b,m)}\left(Q_{k,t}^s - 0.5QL_{k,t}^s\right) = QD_{b,t} \tag{57}$$

$$P_{b,m,k,t}^s - M\left(1 - {z^s}_{k,t}zc_k^s\right) \leq P_{k,t}^s \leq P_{b,m,k,t}^s + M\left(1 - {z^s}_{k,t}zc_k^s\right) \tag{58}$$

$$Q_{b,m,k,t}^s - M\left(1 - {z^s}_{k,t}zc_k^s\right) \leq Q_{k,t}^s \leq Q_{b,m,k,t}^s + M\left(1 - {z^s}_{k,t}zc_k^s\right) \tag{59}$$

$$-P_k^{\max}{z^s}_{k,t}zc_k^s \leq P_{k,t}^s \leq P_k^{\max}{z^s}_{k,t}zc_k^s \tag{60}$$

$$-Q_k^{\max}{z^s}_{k,t}zc_k^s \leq Q_{k,t}^s \leq Q_k^{\max}{z^s}_{k,t}zc_k^s \tag{61}$$

$$\begin{pmatrix} gb_k\sum\limits_{l=1}^{L} k\left(l\right)\Delta\delta_{k,t}^s\left(l\right) \\ -M\left(1 - {z^s}_{k,t}zc_k^s\right) \end{pmatrix} \leq PL_{k,t}^s \leq \begin{pmatrix} gb_k\sum\limits_{l=1}^{L} k\left(l\right)\Delta\delta_{k,t}^s\left(l\right) \\ +M\left(1 - {z^s}_{k,t}zc_k^s\right) \end{pmatrix} \tag{62}$$

$$0 \leq PL_{k,t}^s \leq {z^s}_{k,t}.zc_k^s.\ gb_k\left(\delta_k^{\max}\right)^2 \tag{63}$$

$$\begin{pmatrix} -bg_k \sum_{l=1}^{L} k(l)\,\Delta\delta_{k,t}^{s}(l) \\ -M\left(1 - z^{s}{}_{k,t} zc_k^s\right) \end{pmatrix} \le QL_{k,t}^{s}$$
$$\le \begin{pmatrix} -bg_k \sum_{l=1}^{L} k(l)\,\Delta\delta_{k,t}^{s}(l) \\ +M\left(1 - z^{s}{}_{k,t} zc_k^s\right) \end{pmatrix} \tag{64}$$

$$0 \le QL_{k,t}^{s} \le -z^{s}{}_{k,t}.zc_k^s.\ bg_k\left(\delta_k^{\max}\right)^2 \tag{65}$$

$$\delta_k^{\min} \le \delta_{k,t}^{s} \le \delta_k^{\max} \tag{66}$$

$$\Delta V^{\min} \le \Delta V_{b,t}^{s} \le \Delta V^{\max} \tag{67}$$

$$\begin{pmatrix} -\Delta SP_k^{\max} - \\ M\left(z^{s}{}_{k,t-1} - z^{s}{}_{k,t} + 1\right) zc_k^s \end{pmatrix} \le \delta_{k,t}^{s}$$
$$\le \begin{pmatrix} \Delta SP_k^{\max} + \\ M\left(z^{s}{}_{k,t-1} - z^{s}{}_{k,t} + 1\right) zc_k^s \end{pmatrix} \tag{68}$$

$$\delta_{k,t}^{+s} - \delta_{k,t}^{-s} = \delta_{k,t}^{s} \tag{69}$$

$$\Delta V_{b,t}^{+s} - \Delta V_{b,t}^{-s} = \Delta V_{b,t}^{s} \tag{70}$$

$$T^{s}{}_{k,t} \le T_{\max} \tag{71}$$

$$qs_{k,t} = Ks_{k,t} D_k Qs_{k,t}. \tag{72}$$

Equations (10)–(16) are constraints on EENS with considering the probability of the CB failure. The SCUC problem is scheduled for 24 h of the next day.

C. Solution Methodology of SCUC Problem

Presence of contingency in the problem is one of the requirements. On the other hand, including contingencies in the SCUC problem extends the solving process.

In this article, a three-level Bender's approach is applied, as shown in Fig. 2. This approach decomposes the UC problem into a master problem and two subproblems (subproblem 1 and subproblem 2). The subproblem part in the figure includes both subproblems 1 and 2. Generally, this figure shows the solving process that is employed for both normal conditions and contingencies. The only difference is in security constraints and Bender's cut, which is discussed in the following.

1) Master Problem: In this level constraints on UC, including ramp up/down, minimum uptime, minimum downtime, and power balance constraints are considered.

The objective function of the problem is to minimize generating power costs

$$\min Z^{\mathrm{down}(v)} = \sum_t \sum_g \times \begin{bmatrix} C\left(P^{0(v)}{}_{g,t}\right) + SU_{g,t}(v^{0(v)}{}_{g,t}) \\ +SD_{g,t}(w^{0(v)}{}_{g,t}) + C\Delta r_{g,t}^{s(v-1)} + C_r{}^{(v-1)} + C_l{}^{(v-1)} \end{bmatrix} \tag{73}$$

$$\sum_g P^{0(v)}{}_{g,t} = PD_{b,t} \tag{74}$$

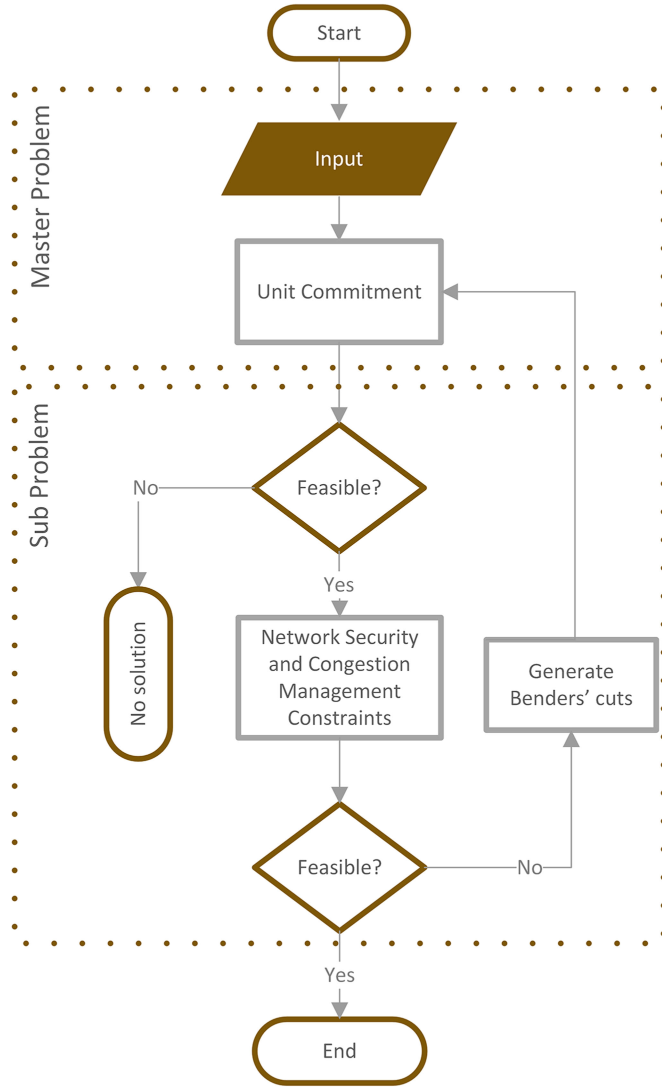

Fig. 2. Benders' decomposition approach diagram.

$$(\text{Using } (48)\text{––}(54) \text{ with consideration of } S = 0) \tag{75}$$

$$P^{0(v)}{}_{g,t} + \max\left[\Delta r^{s(v-1)}{}_{g,t}\right] u^{0(v)}{}_{g,t} \le P_{g,t}^{\max} u^{0(v)}{}_{g,t} \tag{76}$$

$$P^{0(v)}{}_{g,t} + \min\left[\Delta r^{s(v-1)}{}_{g,t}\right] u^{0(v)}{}_{g,t} \ge P_{g,t}^{\min} u^{0(v)}{}_{g,t}. \tag{77}$$

$\max[\Delta r^{s(v-1)}{}_{g,t}]$ and $\min[\Delta r^{s(v-1)}{}_{g,t}]$ are obtained from the solution of the previous iteration and they pick the maximum and minimum values of reserves of the different scenarios. When a contingency occurs, the value of reserve power is computed in subproblem 2. Then, the maximum and minimum values of the reserve power are used in the master problem for the next iteration.

2) Subproblem 1: System security evaluation subproblem 1 contains system security constraints with no contingency. The system security constraints are on: lines' power flow, generator's power considering reserve power, reserve power, TS, transmission lines, voltage angles in buses, and bus voltages. The objective function of the subproblem 1 minimizes the slack variables.

$$\min \sum_{b} \left(SP^{0(v)}{}_{1,b,t} + SP^{0(v)}{}_{2,b,t} \right) + \sum_{n} \left(SQ^{0(v)}{}_{1,b,t} + SQ^{0(v)}{}_{2,b,t} \right) \tag{78}$$

$$\sum_{\forall g(b)} \hat{P}^{0(v)}_{g,t} - \sum_{\forall k(b,m)} \left(P^{0(v)}{}_{k,t} - 0.5PL^{0(v)}{}_{k,t} \right) = PD_{b,t} + SP^{0(v)}{}_{1,b,t} + SP^{0(v)}{}_{2,b,t} - P^{0(v)}{}_{sh_{b,t}} \tag{79}$$

$$\sum_{\forall g(b)} \hat{Q}^{0(v)}_{g,t} + \sum_{\forall k(b,m)} \left(Q^{0(v)}{}_{k,t} - 0.5QL^{0(v)}{}_{k,t} \right) = QD_{b,t} + SQ^{0(v)}{}_{1,b,t} + SQ^{0(v)}{}_{2,b,t} \tag{80}$$

$$((58)-(72) \text{ while } s = 0.) \tag{81}$$

$$P^{0(v)}{}_{g,t} = \hat{P}^{0(v)}_{g,t} \to \gamma^{0(v)}{}_{g,t} \tag{82}$$

$$u^{0(v)}{}_{g,t} = \hat{u}^{0(v)}_{g,t} \to \eta^{0(v)}{}_{g,t} \tag{83}$$

$$z^{0(v)}{}_{k,t} = \hat{z}^{0(v)}_{k,t} \to \mu^{0(v)}{}_{k,t} \tag{84}$$

$$Q^{0(v)}{}_{g,t} = \hat{Q}^{0(v)}_{g,t} \to \lambda^{0(v)}{}_{g,t}. \tag{85}$$

In order to use the Benders' cut instead of network variables ($P^{0(v)}{}_{g,t}$,$u^{0(v)}{}_{g,t}$, etc.), their dual variables must be defined. $\lambda^{0(v)}{}_{g,t}$, $\eta^{0(v)}{}_{g,t}$,$\mu^{0(v)}{}_{k,t}$ and $\gamma^{0(v)}{}_{g,t}$ are dual variables, defined for (82)–(85). These dual variables pertain to Benders' iteration v. The Benders' cut, that is obtained from subproblem, can be written as follows:

$$\sum_{b} \left(SP^{0(c)}{}_{1,b,t} + SP^{0(c)}{}_{2,b,t} \right) + \sum_{n} \left(SQ^{0(c)}{}_{1,b,t} + SQ^{0(c)}{}_{2,b,t} \right) + \sum_{k} \mu^{0(c)}{}_{k,t} \left(z^{0}{}_{k,t} - \hat{z}^{0(c)}_{k,t} \right) + \sum_{g} \times \begin{bmatrix} \gamma^{0(c)}{}_{g,t} \left(P^{0}{}_{g,t} - \hat{P}^{0(c)}_{g,t} \right) \\ +\eta^{0(c)}{}_{g,t} \left(u^{0}{}_{g,t} - \hat{u}^{0(c)}_{g,t} \right) + \lambda^{0(c)}{}_{g,t} \left(Q^{0}{}_{g,t} - \hat{Q}^{0(c)}_{g,t} \right) \end{bmatrix} \le 0, \quad c = 1, \ldots, v-1. \tag{86}$$

3) Subproblem 2: In the contingency evaluation of the third level, the system security with contingencies is checked. The contingencies are generator and transmission line outages

$$Z^{\mathrm{up}(v)} = \left(SP^{s(v)}{}_{1,b,t} + SP^{s(v)}{}_{2,b,t} \right) + \sum_{n} \left(SQ^{s(v)}{}_{1,b,t} + SQ^{s(v)}{}_{2,b,t} \right) + Z^{\mathrm{down}(v)} \tag{87}$$

$$((55) - (72) \text{ while} s > 0) \tag{88}$$

$$\sum_{b} \left(SP^{s(c)}{}_{1,b,t} + SP^{s(c)}{}_{2,b,t} \right) + \sum_{n} \left(SQ^{s(c)}{}_{1,b,t} + SQ^{s(c)}{}_{2,b,t} \right) + \sum_{k} \mu^{s(c)}{}_{k,t} \left(z^{0}{}_{k,t} - \hat{z}^{0(c)}_{k,t} \right) + \sum_{g} \times \begin{bmatrix} \gamma^{s(c)}{}_{g,t} \left(P^{0}{}_{g,t} - \hat{P}^{0(c)}_{g,t} \right) \\ +\eta^{s(c)}{}_{g,t} \left(u^{0}{}_{g,t} - \hat{u}^{0(c)}_{g,t} \right) + \lambda^{s(c)}{}_{g,t} \left(Q^{0}{}_{g,t} - \hat{Q}^{0(c)}_{g,t} \right) \end{bmatrix} \le 0, \quad c = 1, \ldots, v-1. \tag{89}$$

$\lambda^{s(c)}{}_{g,t}$, $\eta^{s(c)}{}_{g,t}$, $\mu^{s(c)}{}_{k,t}$, and $\gamma^{s(c)}{}_{g,t}$ are dual variables for subproblem 2. Since Benders' cut will not be produced for the last iteration, so Benders' cut is generated until iteration $v-1$ [6].

$$\left| Z^{\mathrm{up}(v)} - Z^{\mathrm{down}(v)} \right| \le \varepsilon_1. \tag{90}$$

First, the master problem is executed, and the result is the optimum generator powers, which minimize the costs at the master level. The attained results will be used in the next levels. The second level (subproblem 1) evaluates the system security. If the result that is obtained from the master problem provides the system security, and all the constraints are preserved, that means generated powers and operation cost of the master problem are acceptable.

Otherwise, it means that results that are obtained from the master level are not acceptable and should be changed. To do so, a Benders' cut will be sent to the master level, and master problem will run in the next iteration by considering Benders' cut. This process iterates until the master problem and subproblem become convergent (90). In the third level (subproblem 2), system security considering different contingencies will be evaluated. In this level, such as the previous one, a Benders' cut will be sent to the master level to make it convergent.

V. Simulation Results

In this section, results from implementing the proposed model on 6-bus and large-scale 118-bus IEEE-based test systems [27], for a period of 24 h, are presented.

Moreover, the proposed SCUC model with TS and considering DTLR is compared with the conventional SCUC model. In this article, CPLEX solver in GAMS software [28], [29] is used with a desktop computer with 3.4 GHz processor and 32 GB of RAM.

A. Inputs of the Case Study

The 6-bus test system is shown in Fig. 3. As it is shown in the figure, the system consists of three generating units, three loads, and seven transmission lines. Power generation limitations and total load are presented in Fig. 4. Generators and lines characteristics are presented in Tables I and II. The first, second, and third load, are assumed to be 20%, 40%, and 40% of the total load, respectively. Weather characteristics, including wind speed, solar radiation, and ambient temperature, are from [12]. Conductors' maximum temperature is expected to be 100 °C. Ambient temperature is equal for lines 1 and 2. For lines 3 and 5, it is 3° higher, and for lines 4, 6, and 7, it is 3° lower [13].

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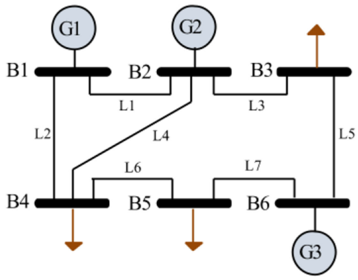

Fig. 3. 6-bus test system.

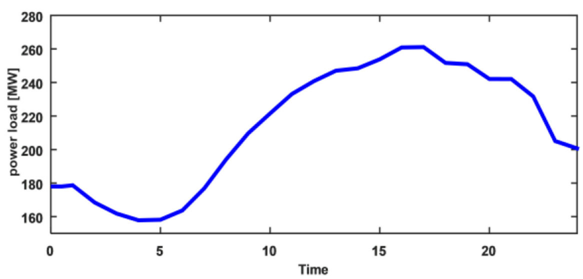

Fig. 4. Load curve of 6-bus system.

TABLE I
GENERATORS DATA FOR 6-BUS SYSTEM

	G1	G2	G3
Energy bid price ($/MWh)	20	23	35
Ramp up/down rate (MW/h)	55	50	20
Start-up cost ($)	100	100	100
P_{max} (MW)	220	200	50
P_{min} (MW)	100	10	10
Q_{max} (MW)	200	70	50
Q_{min} (MW)	-80	-40	-40
Minimum up time (h)	4	3	1
Minimum down time (h)	4	2	1

TABLE II
TRANSMISSION LINES DATA FOR 6-BUS SYSTEM

Line number	From bus	To bus	X_l (pu)	R_l (pu)	Flow limit (MW)
L1	1	2	0.17	0.005	150
L2	1	4	0.258	0.003	150
L3	2	3	0.037	0.022	150
L4	2	4	0.197	0.007	150
L5	3	5	0.018	0.005	150
L6	4	5	0.037	0.002	37
L7	5	6	0.14	0.002	150

B. SCUC Model With TS

Using TS in the SCUC problem significantly improves the system security, technically and economically. When TS operates in the SCUC problem, it prevents congestion in lines with the help of switching. In this case, each line needs a CB to enter or exit the system. The lifetime of these CBs depends on the number of switching. In the SCUC with TS, there is no limit to the number of CB switching. In this case, for some scenarios of TS operation, many switchings are performed to reduce line congestion. That reduces the CB lifetime and has negative influences on the system security. The results of the SCUC model without considering the CB reliability and DTLR are listed in Table III. For each switching (0–1 or 1–0), a switching operation will be counted. Based on the obtained results, in congested lines (4-2 and 5-4), the number of switching is rather high. Since the SCUC problem in static line rating (SLR) mode (DTLR is not considered) is assumed to be in the worst weather conditions, lines' heat losses would increase. Then, lines' power flow and line congestion rise as well, and this matter may lead to more switching. Ultimately, generators reserve power and operation cost will increase.

TABLE III
TS OPERATION IN THE SLR MODE

Line	Number of Switching	Failure Probability (1/24h)	Reliability (1/24 h)	Maintenance cost ($/24h)
2-4	9	0.01213	0.9878	12.13
4-5	14	0.01888	0.9811	18.88

C. SCUC Model With TS, CB Reliability, and DTLR

To improve the TS operation, a limit for the number of switching in a period should be developed. This limitation should reduce congestion and improve the system reliability. The suggested approach to limit the number of switching is involving CB reliability in the SCUC problem with TS. High number of CB switching increases the CB failure probability, which leads to line outages. So generally, it can be concluded that there is a direct relationship between the number of CB switching and EENS. The number of switching is limited to reduce EENS. Since the CB failure imposes some repair costs, by adding it to the objective function, the number of switching will be restricted. Considering DTLR can reduce the number of switching by itself, so the proposed model is compared with the SLR and DTLR-TS modes in number of switching, the CB failure probability, EENS, repair cost, and the operation cost.

Obtained results are given in Tables IV. Results are presented for different scenarios including generator 2 outage and generator 3 outage.

As Table IV indicates, when generator number 2 is out and $n_1 = 0$, the number of switching in the DTLR-TS mode is less than the SLR mode. Considering DTLR in the problem leads to a decrement in thermal losses, which results in reducing the number of switching, compared with static mode. That is why EENS has decreased from 2.7633 to 1.166 and the reliability of CB is improved. Less thermal losses also have shrunk down the operation costs to 1.142×10^5. In Fig. 5, switching in the 118-bus system is illustrated. As mentioned earlier, not only considering DTLR decreases the number of switching, but also considering CB reliability in EENS and operation cost causes positive effects. In Table IV, number of switching for lines 4-2

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TABLE IV
TS OPERATION IN THE SLR MODE

		Line	Number of switching	Failure Probability (1/24h)	Repair Cost ($/24h)	EENS (MWh)	Generation Cost ($)
6 bus system generator 2 is out n_1=0	SLR mode	2-4	9	0.0121	12.13	2.763	1.8314×10^5
		4-5	14	0.0189	18.88		
	DTLR-TS	2-4	6	0.0080	8	1.166	1.1420×10^5
		4-5	4	0.0053	5.3		
	Proposed model	2-4	5	0.0067	6.7	0	1.0886×10^5
		4-5	2	0.0026	2.6		
6 bus system generator 3 is out n_1=0	SLR mode	2-4	12	0.0161	16.1	1.31	1.5564×10^5
		4-5	8	0.0107	10.7		
	DTLR-TS	2-4	10	0.0134	13.4	0.924	1.0670×10^5
		4-5	12	0.0161	16.1		
	Proposed model	2-4	4	0.0053	5.3	0.071	1.0460×10^5
		4-5	8	0.0107	10.7		
6 bus system generator 2 is out n_1= max/2	Proposed model	2-4	5	0.5567	556.7	0	1.1005×10^5
		4-5	4	0.5553	555.3		
6 bus system generator 3 is out n_1= max/2	Proposed model	2-4	5	0.5667	556.7	7.88	10921×10^5
		4-5	2	0.5525	552.5		
118-bus system generator 13 is out n1=0	SLR mode	30	11	0.0148	14.8	678.5	1.0819×10^6
		78	10	0.0134	13.4		
		90	8	0.0107	10.7		
	DTLR-TS	30	9	0.0121	12.13	502.32	1.0025×10^6
		78	9	0.0121	12.13		
		90	7	0.0094	9.43		
	Proposed model	30	6	0.0080	8	233.6	1.0009×10^6
		78	4	0.0053	5.3		
		90	4	0.0053	5.3		
118-bus system generator 13 is out n1= max/2	Proposed model	30	5	0.5567	556.7	20922	1.0118×10^6
		78	3	0.5539	553.9		
		90	4	0.5553	555.3		

is 6 and for lines 5-4 is 4 in the DTLR-TS mode, but in the proposed model *dl* is reduced and the result is five switchings for lines 4-2 and two switchings for lines 5-4.

One of the main points that should not be neglected in the SCUC problem is that this mitigation in the number of switching should also reduce the operation costs. According to the results, operation cost has dropped to 1.0886×10^5 in the proposed model, from 1.1420×10^5 in the DTLR-TS mode.

To be assured about the performance of the proposed model, it is tested when generator number 3 is out and $n_1 = 0$. Results are in Table IV. $n_1 = 0$ implies that all CBs are operating for the first time in this 24-h period. Another assumption is that all CBs have switched half of their expected number of switching before this 24-h period.

Results of this assumption for the SLR mode, the DTLR-TS mode, and the proposed model with different scenarios are presented in Table IV. Naturally in this case, more switching is needed and as a result the CB failure is more probable, compared with when $n_1 = 0$. According to Table IV, the DTLR-TS mode operates better than the SLR mode and number of switching, failure probability of the CB and CB reliability are all finer and yet the proposed model has led to better results among all. As expected, the number of switching in lines 4-2 and 5-4 in the proposed model is less than the DTLR-TS mode. Also, as a result of *dl* reduction, EENS has dropped from 36.01 MWh in the DTLR-TS mode to 7.88 MWh in the proposed model.

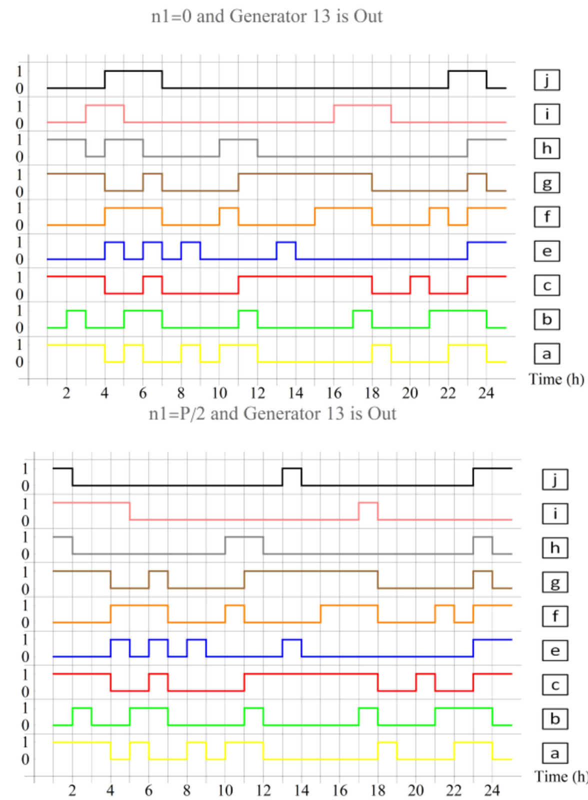

Fig. 5. CB switching for 118-bus system. (a) SLR mode, line 30. (b) SLR mode line 78. (c) SLR mode, line 90. (d) DTLR-TS mode, line 30. (e) DTLR-TS mode, line 78. (f) DTLR-TS mode, line 90. (g) Proposed model, line 30. (h) Proposed model, line 78. (i) Proposed model, line 90.

TABLE V
COMPUTATION TIME FOR THE SLR MODE, DTLR-TS, AND THE PROPOSED MODEL FOR 118-BUS SYSTEM

	Computation Time(sec)	Number of Iteration
SLR	112	23
DTLR-TS	103	20
Proposed Model	98	19

This model is also implemented on a 118-bus system and results are presented in Table IV for a scenario in which generator number 13 is out. Lines 30, 78, and 90 are considered as switching lines. The amount of EENS in larger systems is of great importance and is able to significantly alter the operation cost. As the proposed model contains the repair and maintenance costs in its objective function, it is able to mitigate repairing costs. It is worthy to mention that in case when n_1 is half of the maximum number of switching, CB failure is more probable and applying the model on a longer scheduling horizon leads to more impressive results and the preference of the proposed model in comparison with the DTLR-TS mode and the SRL mode will be bolder. Computation time for different approaches is presented in Table V. The duality gap is set on 0.01 in the codes. Number of variables and equations are presented in Table VI.

TABLE VI
NUMBER OF VARIABLES AND EQUATIONS IN GAMS CODE FOR THE SLR MODE, DTLR-TS, AND THE PROPOSED MODEL FOR 6-BUS SYSTEM

	Variables	Equations
SLR	43,289	468,753
DTLR-TS	42,781	81,670
Proposed Model	40,926	79,479

VI. CONCLUSION

The main challenge in the TS operation is the high number of switching in the system. Since usually there is no limitation for switching, due to high number of switching, reliability will be reduced and CB failure will be more probable. Each line has a CB, so higher failure probability increases the probability of line outage and this has negative influence on the overall system security. In this article, to develop a limitation on the number of switching, the SCUC model with TS is involved with CB reliability and the repair cost of CB failure is also augmented in the objective function. In the proposed model, reducing the number of switching is carried out in order to reduce operation costs. This means that TS operates to reduce operation costs with minimum number of switching. Furthermore, to handle transmission heat losses in the SCUC model, DTLR is employed. This also helps to improve TS performance.

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Morteza Sheikh is currently working toward the Ph.D. degree with the Shiraz University of Technology, Shiraz, Iran.

Jamshid Aghaei (M'12–SM'15) is a Professor with the Shiraz University of Technology, Shiraz, Iran.

Armin Letafat is an Assistant Professor with Islamic Azad University, Kazeroun, Iran.

Mohammad Rajabdorri is currently working toward the Ph.D. degree with the Comillas Pontifical University, Spain.

Taher Niknam is a Professor with the Shiraz University of Technology, Shiraz, Iran.

Miadreza Shafie-Khah (M'13–SM'17) is an Assistant Professor with the University of Vaasa, Vaasa, Finland.

João P. S. Catalão (M'04–SM'12) is a Professor with the Faculty of Engineering, University of Porto, Porto, Portugal, and a Research Coordinator at INESC TEC.