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Computational Simulation Results in Power Systems Operation to Integrate Reliability in the Security Constrained Optimization Problem

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***Abstract*—In order to decrease operation costs in a security constrained unit commitment (SCUC) problem, strategies such as transmission switching (TS) can be utilized. However, having no limit for the switching of circuit breakers (CBs) in the system is troublesome, since a high number of switching increases the failure probability and decreases the reliability of a CB, in addition to resulting in shorter CB lifespans and higher maintenance and operating costs. In this paper, the reliability of CBs is integrated into the SCUC problem with TS to limit its switching. Since the higher reliability of CBs will increase the reliability of the system, it can be inferred that the reliability of CBs will affect the amount of load shedding. A linearization method is presented to linearize the CB reliability equation. Also, an improved linear AC optimal power flow (ILACOPF) with dynamic thermal line rating (DTLR) which considers weather conditions is used in the model to further reduce the number of switching. In order to evaluate the suggested approach, numerical testing is performed for 6-bus and large-scale 118-bus IEEE test systems with different scenarios.**

***Keywords*—computational simulation, power systems operation, reliability, security, optimization.**

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

$P_{sh_{b,t}}$	Amount of load shedding due to CB failure
$P_{b_{b,k,j,t}}$	Amounts of load shedding due to CB that are functions of a binary variable
$P_{g,t}, Q^s_{g,t}, \Delta r^s_{g,t}$	Generator active/reactive/reserve power [p.u]
$P_k^{\max}$	Active power limit for lines [MW]
$\Delta V_b, V_b$	Voltage changes and voltage of each bus [p.u]
$\delta_k, \Delta\delta_k\ (l)$	Phase difference and block of angle difference
δ_k^+, δ_k^-	Non-negative variable for angle difference
$SP_{1,b,t}, SP_{2,b,t}$	Slack variables [p.u]
$SQ_{1,b,t}, SQ_{2,b,t}$	Slack variables [p.u]
$QL_{k,j}, QS_{k,j}$	Load outage caused by CB failure
$a_{b_{k,m,t}}, b_{b_{k,m,t}}$	Coefficients for Piecewise linearized failure probability of CB
B, α	Coefficients related to failure probability of CB
$N_{b_{k,m}}$	Piecewise linearized number of switching
R_g^+, SR_g^+	Maximum ramp up/ramp down rate [MW]
$SU_{g,t}, SD_{g,t}$	Start-up and shut-down cost for generators
$P_g^{\max}, P_g^{\min}$	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)

I. INTRODUCTION

Using Transmission Switching (TS) in Security Constrained Unit Commitment (SCUC) can lead to improvements in system security, voltage stability, and contingency management. Despite these advantages, one main problem of TS is the high number of switching in a specific period. More switching results in higher operation and maintenance costs for circuit breakers (CB). Since any changes in the reliability of a device highly influences the overall reliability of the system [1], a limitation in the number of switching is developed by adding repair and maintenance costs of CBs to the objective function of the problem. To do so, a complete reliability model for CBs based on the number of switching events is added to the problem. 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 AC power flow formulations which will lessen the line heat losses and operating costs [2].

In [3] a real time management is introduced which considers DTLR. In [4] a time series model is proposed to evaluate DTLR. A thorough investigation is made in [5] to ensure the reliable use of DTLR in the system. In [6], TS is used to better handle the contingencies in the system. In [7], the TS is implemented to obtain the *n-1* security criterion and in [8], it is employed to improve power flow and to cope with over-voltages. In [9], TS is implemented on RTS-96 system, where it was shown that choosing switchable lines is one of the challenges in TS studies. In [10] an algorithm is introduced that optimally chooses the switchable lines, but nothing is mentioned regarding the number of switching in lines. The fact that CBs have a finite lifetime is neglected in almost all previous TS studies. There are many studies in the literature that model the reliability of CB. To optimize the TS operation in the power system, a reliability model of CB is needed, which can be obtained from experimental tests or by using real field data. For CBs, due to difficulty and high cost of experimental testing, using real historical data is preferred [11]. Using data from the Swedish transmission system, in [12] a complete reliability model for a specific type of CB is introduced. In [13], data related to CBs reliability is presented. The importance of the CB reliability and its major role in the power system is noted in [11]. To improve the number of switching in TS studies, a reliability model for CB is needed to directly relate the number of switching of CBs with their reliability. TS has been used in various studies and for different purposes. In [14], TS is used to minimize the expected energy not served (EENS). In [15], an optimal transmission switching is introduced considering the reliability of CB. However, the number of switching in transmission lines is neglected in most previous studies and directly putting a limitation on the number of switching in the TS operation is unprecedented. Practically, high number of switching reduces the lifespan of CBs and imposes extra operation costs on the operator.

To the best of the authors' knowledge, the novel contributions of this study can be summarized as follows: 1) Repairing costs for CBs are added to the problem, such that the optimal line switching schedule attained would also reduce the overall costs. 2) A reliability model for CBs as a function of number of switching is employed. 3) Since CB reliability equation is nonlinear, a linear approximation is provided in this paper. 4) DTLR is used in SCUC to reduce thermal losses.

II. MODELING OF CB RELIABILITY

In problems of optimal transmission switching, CBs are used to open or close the transmission lines. CBs, like any other device in the power system, have a limited lifespan which depends on many aspects. The main factor which affects the lifespan of a CB and its reliability is the number of switching. Hazard rate is the failure probability of a component working at age *t*. This probability can be used to determine the reliability of CB. Open-operation, and close-operation locks are critical parts for the reliability of a CB. It is assumed that these two parts are replaced after CB failure and other parts remain. Thus maintenance of the other parts will not affect the overall reliability of the CB [11]. Then in [12], failure of CB based on the number of switching is given by (1).

$$D(N) = \frac{\alpha}{\beta}\left(\frac{N}{\beta}\right)^{\alpha-1} e^{-\left(\frac{N}{\beta}\right)^{\alpha}} \qquad (1)$$

In Eq. (1), *D(N)* is a measure to determine failure of a CB and has no dimensions. N is the number of switching events occurring during period t plus the number of switching events which happened before period t. α and β are constants related to the cause of failure. Therefore, if the number of switching in period t changes, *D(N)* will change too. To calculate *D(N)* for a 24-hour time period in the future, the number of switching events scheduled to happen in that period should be considered.

$$f_K(N_K) = \frac{1}{D}\frac{\alpha}{\beta}\left(\frac{N_K}{\beta}\right)^{\alpha-1} e^{-\left(\frac{N_K}{\beta}\right)^{\alpha}} \qquad (2)$$

Eq. (2) represents failure probability function of the CB based on a number of switching. $f_k(N_k)$ is the failure probability of each CB, D is a failure of a switch in the worst condition (i.e. the maximum number of switching in period t), and N_k is the number of switching of the CB in line k, assuming that only one CB is used for each line. The reliability of the CB is related to its failure probability and is calculated by Eq. (3).

$$R_k = 1 - f_k \qquad (3)$$

R_k represents the reliability of the CB. One objective of this study is to improve the reliability of the CB and the system by alleviating the number of switching. This aim will be met when f_k is closest to zero. In the SCUC with TS, each line has a CB, so CB failure leads to transmission line outage. Therefore, it is concluded that the high probability of CB failure results in transmission line outages. More switching in CBs increases the probability of the failure and that increases the probability of the transmission line outage. On the other hand, the line outage can affect the power balance equation and load shedding. The portion of the EENS which is caused by the CB failure can be determined based on the CB reliability:

$$EENS = \sum_k \sum_b \sum_t f_k \, P_{sh_{b,t}} \qquad (4)$$

where $P_{sh_{b,t}}$ is the amount of load shedding due to the CB failure and EENS is that amount of energy which is not supplied due to the CB failure. Evidently, Eq. (2) and Eq. (4) are non-linear functions and should be linearized. In [13], based on scenario probability, a linear approximation for the EENS is presented. So, Eq. (2) should be rewritten as a function of binary variables:

$$bj_{k,j}, z_{k,t} \longrightarrow binary\ \ variable \qquad (5)$$

$$N = \sum_K \sum_j \left| z_{k,t} - z_{k,t-1} \right| + n_1 \qquad (6)$$

$$N = \sum_j bj_{k,j} \times j + n_1 \qquad \forall_K \qquad (7)$$

$$f_K(N_K) = \frac{1}{D}\frac{\alpha}{\beta}\left(\frac{\sum_j bj_{k,j}\, j + n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{\sum_j bj_{k,j}\, j + n_1}{\beta}\right)^{\alpha}} \qquad (8)$$

$$EENS = \frac{1}{D}\sum_b \sum_k \sum_j \frac{\alpha}{\beta}\left(\frac{bj_{k,j}\, j + n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{bj_{k,j}\, j + n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} \qquad (9)$$

The number of switching is calculated in Eq. (6), where z_k is a binary variable that indicates outage of line k. If z_k equals to 0, line k is out. Otherwise, line k is in.

Eq. (7) can also be used to calculate the number of switching, where bj is a binary variable and j is a constant parameter. A number of switching in a 24-hour time period varies from 0 to 23. Therefore, j can be considered a parameter within 0 and 23. When Eq. (6) and Eq. (7) are equalized, the binary variable will change so that the sum of j parameters of each line would be equal to the number of switching of that line.

The failure probability and EENS are presented in Eq. (8) and Eq. (9), where a number of switching is replaced by (7). Since Eq. (9) has nonlinear terms, therefore it should be linearized to be used in the operation planning problem. The two nonlinear terms in Eq. (9) are a binary-to-continuous variable multiplication, and an exponential-to-continuous variable multiplication. Eq. (10)-(17) are used to linearize these nonlinear terms.

$$EENS = \frac{1}{D}\sum_b\sum_k\sum_j \underbrace{\frac{\alpha}{\beta}\left(\frac{bj_{k,j}\,j+n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{bj_{k,j}\,j+n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}}}_{P_{b_{b,k,j,t}}} \tag{10}$$

$$EENS = \frac{1}{D}\sum_b\sum_k\sum_j\sum_t P_{b_{b,k,j,t}} \tag{11}$$

$$bj_{k,j} = 1 \xrightarrow{constraint\,(8)} P_{b_{b,k,j,t}} = \frac{\alpha}{\beta}\left(\frac{j+n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{j+n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} \tag{12}$$

$$bj_{k,j} = 0 \xrightarrow{constraint\,(8)} P_{b_{b,k,j,t}} = \frac{\alpha}{\beta}\left(\frac{n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} \tag{13}$$

$$\frac{\alpha}{\beta}\left(\frac{n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} - bj_{k,j}M \le P_{b_{b,k,j,t}} \quad \forall_k, \forall_j, \forall_t \tag{14}$$

$$P_{b_{b,k,j,t}} \le \frac{\alpha}{\beta}\left(\frac{n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} + bj_{k,j}M \tag{15}$$

$$\frac{\alpha}{\beta}\left(\frac{j+n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{j+n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} - \left(1-bj_{k,j}\right)M \le P_{b_{b,k,j,t}} \tag{16}$$

$$P_{b_{b,k,j,t}} \le \frac{\alpha}{\beta}\left(\frac{j+n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{j+n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} + \left(1-bj_{k,j}\right)M \tag{17}$$

Failure probability multiplications to the amount of load shedding in Eq. (10), are replaced by P_b, as shown in Eq. (11). According to Eq. (12) and Eq. (13), if binary variable B_j equals 1, P_b is calculated based on Eq. (12). Otherwise, P_b is calculated based on (13). To enable this, constraints (14)-(17) are used. The EENS and EENS cost are calculated based on the failure probability of the CB. In (18), C_r is the EENS cost and $VOLL$ is a large positive number. Since each CB has its repair and maintenance costs, this cost should be added up to the operating costs. Repair and maintenance cost (c_l) of the switch is presented in Eq. (19).

$$C_r = VOLL \times EENS \tag{18}$$

$$C_l = f_K\left(N_K\right) \times C_e \tag{19}$$

In Eq. (20), f_k is replaced based on Eq. (2). Clearly, the equation is nonlinear because of the exponential term. To linearize Eq. (20), a piecewise linearization method is used in Eq. (21)-(24). The values of the function are increasingly similar to a parabola. This function is divided into linear pieces. The equation of linear pieces is presented in Eq. (21), where ab and bb are parameters of the line equation, N_b is the number of switching in each piece, and u_b is a binary variable showing the outage of each piece. The summation of N_b for all pieces must be equal to the total number of switching, so the summation of failure probability of pieces (G_b) is equal to the total failure probability of the switch. Eq (22) represents the limitations of pieces and Eq. (24) represent the limitations of the binary variable u_b.

$$C_l = \frac{1}{D}\frac{\alpha}{\beta}\left(\frac{N_K}{\beta}\right)^{\alpha-1} e^{-\left(\frac{N_K}{\beta}\right)^{\alpha}} \times C_e \tag{20}$$

$$f_K\left(N_K\right) = \frac{1}{D}\sum_m\left(a_{b_{k,m,t}} N_{b_{k,m}} + u_{b_{k,m}} b_{b_{k,m,t}}\right) \tag{21}$$

$$u_{b_{k,m}} N_{b_{k,m}}^{\min} \le N_{b_{k,m}} \le u_{b_{k,m}} N_{b_{k,m}}^{\max} \tag{22}$$

$$\sum_m u_{b_{k,m}} = 1 \tag{23}$$

$$\sum_m N_{b_{k,m}} = N_K \tag{24}$$

$$C_l = \frac{1}{D}\sum_k\sum_m\left(a_{b_{k,m,t}} N_{b_{k,m}} + u_{b_{k,m}} b_{b_{k,m,t}}\right) \times C_e \tag{25}$$

Line losses are modeled as loads in buses and lines power flow are defined as follows:

$$P_k = V_b^2 gb_k - V_b V_m\left(gb_k\cos\delta_k + bg_k\sin\delta_k\right) \tag{26}$$

$$Q_k = -V_b^2\left(bg_k + bg_{k0}\right) + V_b V_m\left(bg_k\cos\delta_k + gb_k\sin\delta_k\right) \tag{27}$$

Equations (26) and (27) have non-linear terms and the following approximations are needed to make them linear.

$$\cos\delta_k \approx 1 \tag{28}$$

$$\sin\delta_k \approx \delta_k \tag{29}$$

Phase differences between buses are very small, so trigonometric parts are simplified. Also, the buses voltage magnitudes are close to 1 p.u. with minor changes:

$$V_b = 1 + \Delta V_b \tag{30}$$

With these approximations, lines power flow equations will be linear and can be defined as follows:

$$P_k \approx \left(1+2\Delta V_b\right)gb_k - \left(1+\Delta V_b+\Delta V_m\right)\left(gb_k + bg_k\delta_k\right) \tag{31}$$

$$Q_k \approx -\left(1+2\Delta V_b\right)\left(bg_k + bg_{k0}\right) + \left(1+\Delta V_b+\Delta V_m\right)\left(bg_k - gb_k\delta_k\right) \tag{32}$$

$$P_{b,m,k} = \left(\Delta V_b - \Delta V_m\right)gb_k - bg_k\delta_k \tag{33}$$

$$Q_{b,m,k} = -\left(1+2\Delta V_b\right)bg_{k0} - \left(\Delta V_b - \Delta V_m\right)bg_k - gb_k\delta_k \tag{34}$$

As mentioned, line losses are modeled as bus loads [15]:

$$PL_k = gb_k\,\delta_k^2 \tag{35}$$

$$QL_k = bg_k\,\delta_k^2 \tag{36}$$

δ_k^2 in Eq. (35) and Eq. (36) is a non-linear term. With a piecewise linear approach these terms can be linearized.

$$\delta_k = \delta_k^+ - \delta_k^- \tag{37}$$

$$\sum_{l=1}^{L} k\,\delta_k(l) = \left|\delta_k\right| = \delta_k^+ - \delta_k^- \tag{38}$$

$$0 \le k\,\delta_k(l) \le \frac{\delta m^{max}}{L} \quad (39)$$

$$0 \le k\,\delta_k(l) \le k\,\delta_k(l-1) \quad (40)$$

$$k(l) = (2l-1)\frac{\delta m^{max}}{L} \quad (41)$$

$$\delta_k^2 = \sum_{l=1}^{L} k(l)\,k\,\delta_k(l) \quad (42)$$

So, a piecewise linearized presentation of line losses in Eq. (43) and Eq. (44) can be written as follows:

$$PL_k = gb_k \sum_{l=1}^{L} k(l)\,k\,\delta_k(l) \quad (43)$$

$$QL_k = -bg_k \sum_{l=1}^{L} k(l)\,k\,\delta_k(l) \quad (44)$$

In this SCUC model, CB reliability is considered as a constraint to reduce the number of switching. Eq. (45) is the objective function of the problem, which minimizes the generation and the load shedding costs. Active and reactive generated power, start-up/shut-down and ramp up/down constraints are presented in Eq. (46)-(52). uc_g^s is the contingency state of unit g, and $u_{g,t}$ is generating unit entry/exit binary variable. The reserve capacity for each generator is shown with $\Delta r_{g,t}^s$ for each scenario. Reserve capacity for each generator is determined with Eq. (53). Eq. (54) is active power balance considering line losses and load shedding. Eq. (55) presents reactive power balance constraint. The way that TS operates for active and reactive powers is presented with inequalities in Eq. (56) and Eq. (57). 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 large positive number. $P_{b,m,k,t}^s$ shows the power flowing through buses b and m. If the line is open to transmit current, $z_{k,t}$ will be 1 and otherwise $z_{k,t}$ will be zero. Lines' power flow is $P_{b,m,k,t}^s$. Constraints in Eq. (58) and Eq. (59) specify the lines power flow limitations. Line losses are included for this power flow. Constraints on active and reactive power are presented in Eq. (60)-(63). In this power flow, bus voltage changes amplitude and bus voltage angle limitations are also considered and defined as in Eq. (64)-(68). Heat balance constraints in lines are addressed in Eq. (69). In this equation, time is divided into one hour periods and wind speed is supposed to be low. Eq. (70)-(73) are associated with heat losses. Eq. (74)-(80) are constraints on EENS with the failure probability of CB. SCUC problem is scheduled for 24 hours of the next day.

$$\min Z^{down} = \sum_t \sum_g \left[C(P_{g,t}) + SU_{g,t} + SD_{g,t} + C\Delta r_{g,t}^s + C_r + C_l \right] \quad (45)$$

$$P_g^{min} u_{g,t} uc_g^s \le P_{g,t} + \Delta r_{g,t}^s \le P_g^{max} u_{g,t} uc_g^s \quad (46)$$

$$Q_g^{min} u_{g,t} uc_g^s \le Q_{g,t}^s \le Q_g^{max} u_{g,t} uc_g^s \quad (47)$$

$$v_{g,t} - w_{g,t} = u_{g,t} - u_{g,t-1} \quad (48)$$

$$\sum_{t'=t-UT_g+1}^{t} v_{g,t'} \le u_{g,t}, \quad \forall g, t \in \{UT_g, \dots, T\} \quad (49)$$

$$\sum_{t'=t-DT_g+1}^{t} w_{g,t'} \le 1 - u_{g,t}, \quad \forall g, t \in \{DT_g, \dots, T\} \quad (50)$$

$$P_{g,t} - P_{g,t-1} \le R_g^{+} u_{g,t-1} + R_g^{SU} v_{g,t} \quad (51)$$

$$P_{g,t-1} - P_{g,t} \le R_g^{+} u_{g,t} + R_g^{SU} w_{g,t} \quad (52)$$

$$-SR_g^{+} \le \Delta r_{g,t}^s \le SR_g^{+} \quad (53)$$

$$\sum_{\forall g(b)} \left(P_{g,t} + \Delta r_{g,t}^s\right) - \sum_{\forall k(b,m)} \left(P_{k,t}^s + 0.5 PL_{k,t}^s\right) = PD_{b,t}^s - P^s{}_{sh_{b,t}} \quad (54)$$

$$\sum_{\forall g(b)} Q_{g,t}^s + \sum_{\forall k(b,m)} \left(Q_{k,t}^s - 0.5 QL_{k,t}^s\right) = QD_{b,t} \quad (55)$$

$$P_{b,m,k,t}^s - M\left(1 - z_{k,t} zc_k^s\right) \le P_{k,t}^s \le P_{b,m,k,t}^s + M\left(1 - z_{k,t} zc_k^s\right) \quad (56)$$

$$Q_{b,m,k,t}^s - M\left(1 - z_{k,t} zc_k^s\right) \le Q_{k,t}^s \le Q_{b,m,k,t}^s + M\left(1 - z_{k,t} zc_k^s\right) \quad (57)$$

$$-P_k^{max}.z_{k,t}.zc_k^s \le P_{k,t}^s \le P_k^{max}.z_{k,t}.zc_k^s \quad (58)$$

$$-Q_k^{max}.z_{k,t}.zc_k^s \le Q_{k,t}^s \le Q_k^{max}.z_{k,t}.zc_k^s \quad (59)$$

$$\begin{pmatrix} gb_k \sum_{l=1}^{L} k(l)\,k\,\delta_{k,t}^s(l) \\ -M\left(1 - z_{k,t} zc_k^s\right) \end{pmatrix} \le PL_{k,t}^s \le \begin{pmatrix} gb_k \sum_{l=1}^{L} k(l)\,k\,\delta_{k,t}^s(l) \\ +M\left(1 - z_{k,t} zc_k^s\right) \end{pmatrix} \quad (60)$$

$$0 \le PL_{k,t}^s \le z_{k,t}.zc_k^s.gb_k \left(\delta_k^{max}\right)^2 \quad (61)$$

$$\begin{pmatrix} -bg_k \sum_{l=1}^{L} k(l)\,k\,\delta_{k,t}^s(l) \\ -M\left(1 - z_{k,t} zc_k^s\right) \end{pmatrix} \le QL_{k,t}^s \le \begin{pmatrix} -bg_k \sum_{l=1}^{L} k(l)\,k\,\delta_{k,t}^s(l) \\ +M\left(1 - z_{k,t} zc_k^s\right) \end{pmatrix} \quad (62)$$

$$0 \le QL_{k,t}^s \le -z_{k,t}.zc_k^s.bg_k \left(\delta_k^{max}\right)^2 \quad (63)$$

$$\delta_k^{min} \le \delta_{k,t}^s \le \delta_k^{max} \quad (64)$$

$$\Delta V^{min} \le \Delta V_{b,t}^s \le \Delta V^{max} \quad (65)$$

$$\begin{pmatrix} -\Delta SP_k^{max} - \\ M\left(z_{k,t-1} - z_{k,t} + 1\right) zc_k^s \end{pmatrix} \le \delta_{k,t}^s \le \begin{pmatrix} \Delta SP_k^{max} + \\ M\left(z_{k,t-1} - z_{k,t} + 1\right) zc_k^s \end{pmatrix} \quad (66)$$

$$\delta_{k,t}^{+^s} - \delta_{k,t}^{-^s} = \delta_{k,t}^s \quad (67)$$

$$\Delta V_{b,t}^{+^s} - \Delta V_{b,t}^{-^s} = \Delta V_{b,t}^s \quad (68)$$

$$mC_{pk}\left(T^s{}_{k,t+1} - T^s{}_{k,t}\right) = \Delta_t \begin{pmatrix} ql_{k,t}^s\left(T^s{}_{k,t}\right) + qs_{k,t}^s \\ -qc_{k,t}^s\left(T^s{}_{k,t}\right) - qr_{k,t}^s\left(T^s{}_{k,t}\right) \end{pmatrix} \quad (69)$$

$$T^s{}_{k,t} \le T_{max} \quad (70)$$

$$qs_{k,t} = Ks_{k,t} D_k Qs_{k,t} \quad (71)$$

$$qr_{k,t}^s\left(T^s{}_{k,t}\right) = K_{k,t}^r \sum_j \left(a_{k,j,t} Tr_{k,j,t}^s + ur_{k,j,t}^s b_{k,j,t}\right) \quad (72)$$

$$qc_{k,t}^s\left(T^s{}_{k,t}\right) = \left[1.01 + 0.0372\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.52}\right] kf\,K_{angle}\left(T^s{}_{k,t} - T^\alpha{}_{k,t}\right) \quad (73)$$

$$EENS = \frac{1}{D} \sum_b \sum_k \sum_j \sum_t P_{b_{b,k,j,t}} \quad (74)$$

$$N = \sum_K \sum_j \left| z_{k,t} - z_{k,t-1} \right| + n_1 \quad (75)$$

$$N = \sum_j bj_{k,j}\, j + n_1 \qquad \forall_K \quad (76)$$

$$\frac{\alpha}{\beta}\left(\frac{n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} - bj_{k,j} M \le P_{b_{b,k,j,t}} \quad \forall_k, \forall_j, \forall_t \quad (77)$$

$$P_{b_{b,k,j,t}} \le \frac{\alpha}{\beta}\left(\frac{n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} + bj_{k,j} M \quad (78)$$

$$\frac{\alpha}{\beta}\left(\frac{j+n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{j+n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} - \left(1 - bj_{k,j}\right) M \le P_{b_{b,k,j,t}} \quad (79)$$

$$P_{b_{b,k,j,t}} \le \frac{\alpha}{\beta}\left(\frac{j+n_1}{\beta}\right)^{\alpha-1} e^{-\left(\frac{j+n_1}{\beta}\right)^{\alpha}} P_{sh_{b,t}} + \left(1-bj_{k,j}\right)M \tag{80}$$

A. Solving the SCUC Problem

Contingencies should be examined to determine the reliability of the model. However, including contingencies in SCUC problem extends the solution process and computation time. In this paper, a tri-level Bender's approach is employed. This approach decomposes the UC problem into a master problem and two sub-problems (sub-problem 1 and sub-problem 2). The flowchart of the SCUC problem has been illustrated in Fig. 1. First, the master problem is executed to obtain the optimum generator powers which minimize the costs in the master level. The second level (sub-problem 1) evaluates the system security. If the result that is attained from the master problem holds the system security requirements, and preserves all the constraints, the generated powers and operation cost of the master problem are acceptable. Otherwise, it means that the results of master level should be changed. To do so, a Bender's cut is sent to the master level to get the new results. This process iterates until the convergence of master problem and sub-problem. In the third level (sub-problem 2), system security, the case of different contingencies will be evaluated. Here, bender's cuts are also generated to make it convergent. In the next subsections, the formulation of each level is presented.

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

$$MinZ^{down} = \sum_{t}\sum_{g}\left[C\left(P_{g,t}\right) + SU_{g,t} + SD_{g,t} + C\Delta r^{s}_{g,t} + C_r + C_l\right] \tag{81}$$

$$\sum_{g} P_{g,t} = PD_{b,t} \tag{82}$$

$(58-64)\ \ for\ \ s=0$ (Using equations 58-64 with consideration of S=0) (83)

$$P_{g,t} + max\left[\Delta r_{g,t}\right]u_{g,t} \le P^{max}_{g,t}u_{g,t} \tag{84}$$

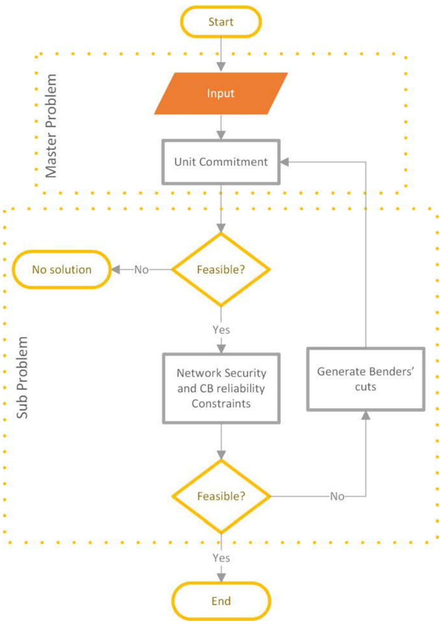

Fig. 1. Flowchart of proposed model of SCUC with CB reliability.

$$P_{g,t} + min\left[\Delta r_{g,t}\right]u_{g,t} \le P^{max}_{g,t}u_{g,t} \tag{85}$$

– *Sub-problem: System security evaluation with contingency*

The system security constraints are on: lines power flow, generators power considering reserve power, transmission switching, transmission lines, voltage angles in buses, and bus voltages. The objective function of the sub-problem minimizes the slack variables.

$$\min \sum_{b}\left(SP_{1,b,t} + SP_{2,b,t}\right) + \sum_{n}\left(SQ_{1,b,t} + SQ_{2,b,t}\right) \tag{86}$$

$$\sum_{\forall g(b)} \hat{P}_{g,t} - \sum_{\forall k(b,m)}\left(P_{k,t} - 0.5PL_{k,t}\right) = PD_{b,t} + SP_{1,b,t} - SP_{2,b,t} - P^{s}_{sh_{b,t}} \tag{87}$$

$$\sum_{\forall g(b)} \hat{Q}_{g,t} + \sum_{\forall k(b,m)}\left(Q_{k,t} - 0.5QL_{k,t}\right) = QD_{b,t} + SQ_{1,b,t} - SQ_{2,b,t} \tag{88}$$

(Using equations 53-73 with consideration of S=0 and Using equations 74-80) (89)

$$P_{g,t} = \hat{P}_{g,t} \rightarrow \gamma_{g,t} \tag{90}$$

$$u_{g,t} = \hat{u}_{g,t} \rightarrow \eta_{g,t} \tag{91}$$

$$z_{k,t} = \hat{z}_{k,t} \rightarrow \mu_{k,t} \tag{92}$$

$$Q_{g,t} = \hat{Q}_{g,t} \rightarrow \lambda_{g,t} \tag{93}$$

where $\lambda_{g,t}$, $\eta_{k,t}$, and $\gamma_{g,t}$ are defined as dual variables in Eq. (90)-(93). Then, these duals are used to generate Bender's cuts. The Bender's cuts obtained can be written as follows:

$$\begin{aligned}&\left(SP_{1,b,t} + SP_{2,b,t}\right) + \sum_{n}\left(SQ_{1,b,t} + SQ_{2,b,t}\right) + \sum_{k}\mu_{k,t}\left(z_{k,t} - \hat{z}_{k,t}\right)\\ &+\sum_{g}\left[\gamma_{g,t}\left(P_{g,t} - \hat{P}_{g,t}\right) + \eta_{g,t}\left(u_{g,t} - \hat{u}_{g,t}\right) + \lambda_{g,t}\left(Q_{g,t} - \hat{Q}_{g,t}\right)\right] \le 0\end{aligned} \tag{94}$$

III. Computational Simulation Results

In this section, results from implementing the proposed model on 6-bus and large-scale 118-bus IEEE test systems [16], for a period of 24 hours are presented. Moreover, the proposed SCUC model with TS and considering DTLR is compared with the conventional SCUC model. In this paper, the CPLEX solver in GAMS software is used with a desktop computer with 3.4 GHz processor and 32 GB of RAM. The 6-bus test system consists of 3 generating units, 3 loads, and 7 transmission lines. Power generation limitations, total load, and line characteristics are provided in [14]. The first, second, and third load are assumed to be 20%, 40%, and 40% of the total load, respectively. Conductors' maximum temperature is expected to be 100 . Ambient temperature is equal for lines 1 and 2. For lines 3 and 5, it is 3 degrees higher, and for lines 4, 6 and 7, it is 3 degrees lower. Integrating the TS into the SCUC problem prevents congestion, therefore the system security is improved both technically and economically. To enable this, all lines need a CB so that they can switch on or off as required.

The method for applying a limitation on the number of switching is to integrate the CB reliability into the SCUC problem with the TS. Applying a limit on the number of switching decreases congestion, increases the reliability of the system, and improves the TS operation accordingly. For a high number of switching, the CB failure probability will increase which can cause line outages and higher EENS. To better compare the studied approaches, the failure probabilities of different cases are illustrated in Fig. 2. The repair cost of the CB is added to the objective function, to limit the number of switching. Different modes are compared in Table I, including Static Line Rating (SLR), DTLR-TS, and the proposed model.

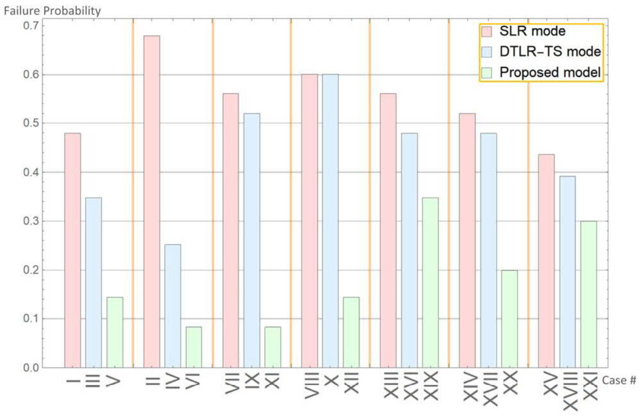

Fig. 2. Failure probability for different cases.

Various scenarios including generator 2 outage, and generator 3 outage, are studied. Since DTLR mitigates the thermal losses, the number of switching in DTLR-TS mode is lower than SLR mode, as shown in the Table I. The lower number of switching resulted in the EENS to decrease from 6.401 to 5.098, and increased the reliability of the system. Also, because of lower thermal losses, the operation costs are decreased to 1.142×10^5. Considering the CB reliability alongside with the DTLR improves the number of switching, EENS, and operation costs, as discussed earlier. The number of switching for lines 4-2 and 5-4 are 6 and 4, respectively, in the DTLR-TS mode. These numbers are decreased to 2 and 1 for lines 4-2 and 5-4, respectively, in the proposed model, since f_k is reduced. This reduction in the number of switching should also lead to operation cost reduction.

As presented in the results, operation cost for DTLR-TS mode is 1.142×10^5, and then it has decreased to 1.098×10^5 for the proposed model. The results for the other scenario where generator number 3 is out is also provided in Table I. These results show a significant decrease in the number of switching for the proposed model. Also, the CB failure and line outage increases the EENS. Here, the amounts of EENS are 1.31, 0.924, and 0.348 for the SLR mode, DTLR-TS mode, and the proposed model, respectively, which shows a significant reduction in the amount of the EENS for the proposed model. Operation costs for each approach are also shown in the table. These results indicate a desirable decrease in operating costs for the proposed model. This model is also implemented on a 118-bus system and results are presented in Table I for a scenario in which generator number 13 is out. Lines 30, 78 and 90 are considered as switchable lines. The amount of EENS in larger systems is of great importance and significantly alters the operation cost. As the proposed model contains the repair and maintenance costs in its objective function, it is able to mitigate repairing costs.

IV. Conclusions

Generally, no limitation is set on the number of switching that happens during TS operation. Hence, a high number of switching will occur leading to a higher failure probability of CBs and line outage, and lower reliability. The overall security of the system will decrease accordingly. In this paper, in order to limit the number of switching, the CB reliability is integrated into the SCUC problem with TS and the repair costs of the CB are added to the objective function. This enables TS to reduce operating costs with a lower number of switching.

TABLE I. Comparing TS Operation in SLR Mode, DTLR-TS and Proposed Model with Different Scenarios

		Case #	Line	Number of switching	Failure Probability	EENS (MWh)	Cost ($)
bus system (generator 2 is out)	*SLR mode*	I	2-4	9	0.479	6.401	1.8314×10^5
		II	4-5	14	0.679		
	DTLR-TS	III	2-4	6	0.347	5.098	1.142×10^5
		IV	4-5	4	0.251		
	Proposed model	V	2-4	2	0.144	0	1.098×10^5
		VI	4-5	1	0.083		
6 bus system (generator 3 is out)	*SLR mode*	VII	2-4	11	0.561	1.31	1.5564×10^5
		VIII	4-5	12	0.601		
	DTLR- TS	IX	2-4	10	0.52	0.924	1.0675×10^5
		X	4-5	12	0.601		
	Proposed model	XI	2-4	1	0.083	0.348	1.0578×10^5
		XII	4-5	2	0.144		
118-bus system (generator 13 is out)	*SLR mode*	XIII	30	11	0.561	678.5	1.08189×10^6
		XIV	78	10	0.52		
		XV	90	8	0.436		
	DTLR- TS	XVI	30	9	0.479	512.75	1.0037×10^6
		XVII	78	9	0.479		
		XVIII	90	7	0.392		
	Proposed model	XIX	30	6	0.347	205.9	1.00165×10^6
		XX	78	4	0.199		
		XXI	90	4	0.3		

Acknowledgment

J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under POCI-01-0145-FEDER-029803 (02/SAICT/2017).

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