# Preventive N-1 Security-Constrained Optimal Transmission Network Reconfiguration

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***Abstract*—The growing complexity of power system operation, driven by increasing load demand and renewable generation variability, challenges Transmission System Operators (TSOs) in maintaining grid security. To comply with network constraints, TSOs tend to leverage their own grid assets relying on cost-free topological reconfiguration actions. In this context, a deterministic preventive N-1 Security-Constrained Optimal Transmission Network Reconfiguration (SCOTNR) problem is proposed as a congestion management support tool for system operators, so that it can be used to derive N-1 secure operative conditions following any single line contingency. The optimization framework is solved through Mixed-Integer Linear Programming techniques for modified IEEE 14-, 39- and 118-Bus test systems.**

***Index Terms*—Mixed-Integer Linear Programming, N-1 Security, Optimal Transmission Network Reconfiguration, Preventive Congestion Management, Topology Control.**

## I. Introduction

Optimal Transmission Network Reconfiguration (OTNR) is a complex combinatorial Mixed-Integer Nonlinear Programming (MINLP) problem typically used to determine the optimal switching actions for improving grid operation. Furthermore, other transmission assets such as phase shifting transformers (PSTs) can be controlled by system operators for congestion management (CM) purposes, either simultaneously with the generating units dispatch.

Most OTNR models in the literature extend the well-known Optimal Power Flow (OPF) [1] and Unit Commitment problems [2], demonstrating how controlling the grid topology while dispatching generation can positively reduce system costs, still ensuring a secure operation.

The majority of studies only consider transmission line switching [1]–[5] and model the grid neglecting the substation details, where the electrical components are connected to the busbars by means of circuit breakers (CBs) and disconnectors. Substation reconfiguration (SR) is less addressed, often tackled employing Mixed-Integer Linear Programming (MILP) techniques when implemented for CM [6]–[8]. These methods formulate deterministic OTNR problem using DC load flow (DCLF) assumptions. Although there are well-established solution methods to integrate N-1 security constraints [6]–[10], this still poses computational challenges in terms of scalability even under DC approximations, requiring the adoption of decomposition techniques to make the problem treatable.

In particular, [7] highlights the importance of formulating a preventive security-constrained OTNR (SCOTNR) model that derives an optimal topology which ensures (N-1) secure operation for any possible contingencies without the need for corrective actions. However, due to its complexity, the preventive SCOTNR problem may yield insecure solutions in small systems or result in an excessive number of switching operations in larger networks, even when both cost-free (switching) and costly (generation dispatch) resources are considered.

In this work, a deterministic MILP preventive N-1 SCOTNR problem is formulated in a comprehensive framework where cost-free control actions (i.e., line switching, SR, and PSTs operation) are coordinated with non cost-free ones (i.e., generation dispatch and load shedding) taking into account N and N-1 security constraints. The optimization problem considers transmission lines connection status, busbar couplers, and disconnectors in substations, as well as PST tap settings as cost-free integer control variables that can be jointly optimized with remunerative control actions. A Column-and-Constraint Generation (C&CG) iterative solution algorithm is also introduced to address the computational challenges related to the problem size and combinatoriality. The methodology is tested on IEEE 14-, 39- and 118-Bus test cases, modified to include double-bus single breaker substations. The overall problem is tackled through a Python-DIgSILENT PowerFactory co-simulation approach, which is proved to reduce substantially the computational effort.

## II. Preventive N-1 SCOTNR Formulation

The preventive N-1 SCOTNR problem can be compactly formulated in the following general form:

$$\begin{aligned} \min_{\boldsymbol{x}_0,\ldots,\boldsymbol{x}_c,\boldsymbol{u}_0} \quad & f_0(\boldsymbol{x}_0,\boldsymbol{u}_0) \\ \text{subject to:} \quad & \boldsymbol{g}_c(\boldsymbol{x}_c,\boldsymbol{u}_0)=\boldsymbol{0}, \quad \forall c \geq 0 \\ & \boldsymbol{h}_c(\boldsymbol{x}_c,\boldsymbol{u}_0)\leq \boldsymbol{0}, \quad \forall c \geq 0 \end{aligned} \tag{1}$$

where $f_0(\boldsymbol{x}_0,\boldsymbol{u}_0)$ is the objective function, $\boldsymbol{g}_c$ (resp. $\boldsymbol{h}_c$) are the equality (resp. inequality) constraints for the $c$-th contingency state (with $c=0$ corresponds to the base case), $\boldsymbol{x}$ and $\boldsymbol{u}$ represent the dependent variables and control variables, respectively. The first ($\boldsymbol{x}_c$) are referred to each contingency condition, whereas $\boldsymbol{u}_0$ must be the same $\forall c \geq 0$, such that

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the grid is secure under both N and N-1 conditions and no corrective actions will be needed in the post-contingency states.

In general, $f_0$ aims to minimize system costs, the topological operations (TOs), such as number of switched-off lines, splitted substations, and PSTs tap positions from the initial operating condition, and load shedding (LS):

$$\min_{\boldsymbol{u}_0} \sum_{g\in\mathcal{G}}\sum_{n=1}^{2} c_g \cdot P_{g,n} + C^{voll}\sum_{d\in\mathcal{D}}\sum_{n=1}^{2} P_{d,n}^{LS} + \sum_{l\in\mathcal{L}}\frac{w_l}{2}(1-\sigma_l)^2 + \sum_{k\in\mathcal{K}}\frac{w_k}{2}(1-\sigma_k)^2 + \sum_{t\in\mathcal{T}}\frac{w_t}{2}(\tau_t)^2 \quad (2)$$

where $c_g$ are the generation costs, whereas $C^{voll}$ the penalty cost for Value of Lost Load. This latter is specifically introduced to prioritize TOs and generation dispatch over LS actions. A high penalty value is assigned to $C^{voll}$ in order to limit as much as possible the amount of power not supplied. TOs, instead, are cost-free control actions, so the last three terms in (2) were introduced to prevent unnecessary switching operations. The weights coefficients $w$ are chosen sufficiently small so that the control effort due to switching and PSTs operations is always negligible with respect to generation rescheduling or LS.

The following decision variables $\boldsymbol{u}_0$ can be defined:

$$\boldsymbol{u}_0 = [\boldsymbol{P_{g,n}}, \boldsymbol{P_{d,n}^{LS}}, \boldsymbol{\sigma_l}, \boldsymbol{\sigma_k}, \boldsymbol{\sigma_{b,s}}, \boldsymbol{\sigma_{g,s}}, \boldsymbol{\sigma_{d,s}}, \boldsymbol{\tau_t}]^\top \quad (3)$$

where $P_{g,n}$ is the active power produced by generator $g$ on bus $n$, $P_{d,n}^{LS}$ is the load shedding active power. The others are integer variables, with $\sigma$ related to switching binary decisions and $\tau_t \in \mathbb{Z}$ the PST tap step. In particular, $\sigma_l$ and $\sigma_k$ represent the line $l$ and busbar coupler $k$ connection states, respectively, taking the value 1 when in-service (0 otherwise), whereas the other variables represent the connection of an element to busbar 1 (or 2) in a substation $s$. In fact, for a branch $b \in \mathcal{B}$ (line $l$ or transformer $t$) connected between two substations $i$ and $j$, $\sigma_{b,s}$ takes 0 if $b$ is connected to busbar 1 in the substation $s \in \{i,j\}$, 1 if connected to busbar 2. The variables $\sigma_{g,s}$ and $\sigma_{d,s}$ are introduced as for $\sigma_{b,s}$ but refer to generators ($g \in \mathcal{G}$) and loads ($d \in \mathcal{D}$), respectively.

To represent typical configurations of transmission busbars, considering that the electrical components in a bulk power system are interconnected by means of switch protection devices (i.e., CBs and disconnectors), a general double-bus single breaker substation model was adopted. The scheme, shown in Fig. 1, permits to represent the topological relationships within the optimization framework.

Assuming that each substation $s \in \mathcal{S}$ consists of two busbars $n_s \in \{1,2\}$ connected by a coupler $k \in \mathcal{K}$, each single-terminal element is connected via a CB and two disconnectors, whereas each two-terminal component has a CB and two disconnectors on each side.

### A. Connection of transmission branches between substations

The following constraints are formulated for each branch $\forall b \in \mathcal{B}$ and for each contingency case $\forall c \geq 0$. For the sake of simplicity, only transmission line contingencies are considered. Therefore, a binary parameter $\gamma_l^c$ can be defined for each line $l$ and contingency case $c$, equal to 0 if $l$ is open in the contingency state $c > 0$, 1 otherwise.

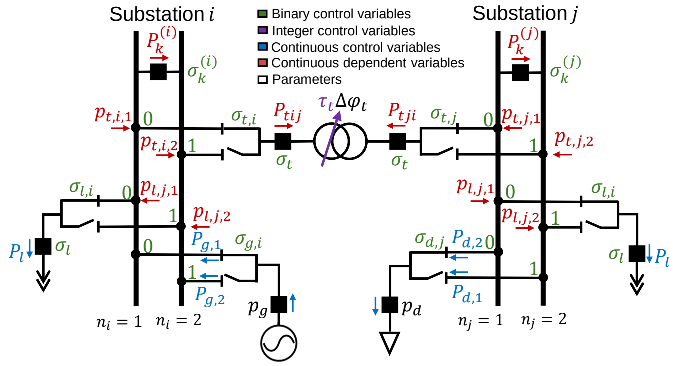


Fig. 1. General Double-Bus Single Breaker substation model: connection modes of transmission branches, generators and loads.

In each contingency case, the active power flow $P_{bij}^c$ on a generic branch $b$ is the sum of two contributions, $p_{b,s,1}^c$ and $p_{b,s,2}^c$, depending on whether connected to busbar 1 or busbar 2 on the side $s$:

$$P_{bij}^c = p_{b,s,1}^c + p_{b,s,2}^c; \quad \forall s \in \{i,j\} \quad (4)$$

$$-\bar{P}_b\gamma_b^c(1-\sigma_{b,s}) \leq p_{b,s,1}^c \leq \bar{P}_b\gamma_b^c(1-\sigma_{b,s}); \quad \forall s \in \{i,j\} \quad (5)$$

$$-\bar{P}_b\gamma_b^c\sigma_{b,s} \leq p_{b,s,2}^c \leq \bar{P}_b\gamma_b^c\sigma_{b,s}; \quad \forall s \in \{i,j\} \quad (6)$$

where $\bar{P}_b$ is the branch rating. Denoting by $\theta_{b,s}^c$ the voltage angles at the ends of a branch (with $s \in \{i,j\}$), and by $\theta_{s,n}^c$ (with $n \in \{1,2\}$) the voltage angle on busbar $n$ in the substation $s$, this latter assumes the value of $\theta_{s,1}^c$ or $\theta_{s,2}^c$, depending on which branch disconnector is closed at each end:

$$-\bar{\theta}\sigma_{b,s} \leq \theta_{b,s}^c - \theta_{s,1}^c \leq \bar{\theta}\sigma_{b,s} \quad (7)$$

$$-\bar{\theta}\cdot(1-\sigma_{b,s}) \leq \theta_{b,s}^c - \theta_{s,2}^c \leq \bar{\theta}\cdot(1-\sigma_{b,s}) \quad (8)$$

where $\bar{\theta}$ is the upper bound for voltage angle.

### B. Line Switching Constraints

Assuming that only transmission lines can be switched-off, while transformers can only change connection busbar if a substation should be split, $p_{l,s,n}^c$ and $\sigma_{l,s}$ are linked to $\sigma_l$ by the following constraints, $\forall l \in \mathcal{L} \land c \geq 0$:

$$-\bar{P}_l\gamma_l^c\sigma_l \leq p_{l,s,n}^c \leq \bar{P}_l\gamma_l^c\sigma_l; \quad \forall s \in \{i,j\}, \forall n \in \{1,2\} \quad (9)$$

$$\sigma_l - \sigma_{l,s} \geq 0 \quad \forall s \in \{i,j\} \quad (10)$$

Moreover, on/off constraints can be formulated choosing a big-M $M_l$ as a real number large enough to make them non-binding when $\sigma_l = 0$:

$$-M_l(2-\sigma_l-\gamma_l^c) \leq b_l(\theta_{l,i}^c - \theta_{l,j}^c) - P_{lij}^c \quad (11)$$

$$b_l(\theta_{l,i}^c - \theta_{l,j}^c) - P_{lij}^c \leq M_l(2-\sigma_l-\gamma_l^c) \quad (12)$$

$$-\bar{P}_l\gamma_l^c\sigma_l \leq P_{lij}^c \leq \bar{P}_l\gamma_l^c\sigma_l \quad (13)$$

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A practical and effective method for computing $M_l$ is provided in [11], where tight values can be efficiently pre-computed by using graph theory and Dijkstra's shortest path algorithms.

### C. Phase Shifter Transformers (PSTs) Constraints

Regarding transformers, (11)-(13) are formulated as equality constraints according to DCLF. Considering an ideal PST with a limited number of tap positions and a voltage angle step $\Delta\varphi_t$ per tap, the following relations can be written:

$$\underline{\tau}_t \leq \tau_t \leq \overline{\tau}_t; \quad \forall t \in \mathcal{T} \tag{14}$$

$$P^c_{tij} = b_t(\theta^c_{t,i} - \theta^c_{t,j} \mp \tau_t \Delta\varphi_t); \quad \forall t \in \mathcal{T}, c \geq 0 \tag{15}$$

$$P^c_{tji} = b_t(\theta^c_{t,j} - \theta^c_{t,i} \pm \tau_t \Delta\varphi_t); \quad \forall t \in \mathcal{T}, c \geq 0 \tag{16}$$

$$-\bar{P}_t \leq P^c_{tij} \leq \bar{P}_t; \quad \forall t \in \mathcal{T}, c \geq 0 \tag{17}$$

$$-\bar{P}_t \leq P^c_{tji} \leq \bar{P}_t; \quad \forall t \in \mathcal{T}, c \geq 0 \tag{18}$$

where (14) limits the PST tap positions within the bounds. The sign of $\tau_t\Delta\varphi_t$ in (15) and (16) depends on which side of the transformer the tap changer is located, (17) and (18) are security constraints.

### D. Substation Splitting Constraints

For each contingency case $c$, in each substation $s$, the voltage angles on the busbars must be equal when the coupler $k$ is closed ($\sigma^s_k = 1$), and are otherwise unconstrained according to the chosen big-M $M_\theta$:

$$-M_\theta \cdot (1 - \sigma^s_k) \leq \theta^c_{s,1} - \theta^c_{s,2} \leq M_\theta \cdot (1 - \sigma^s_k); \quad \forall s \in \mathcal{S} \tag{19}$$

The active power flow $p^c_k$ through the coupler $k$ follows the Big-M rules, $\forall k \in \mathcal{K}$:

$$-M_k(1 - \sigma^s_k) \leq b_k(\theta^c_{s,1} - \theta^c_{s,2}) - p^c_k \leq M_k(1 - \sigma^s_k) \tag{20}$$

$$-M_k\sigma^s_k \leq p^c_k \leq M_k\sigma^s_k \tag{21}$$

### E. System Constraints

In order to integrate power flow equations, system constraints include the active power balance at each busbar in both pre-contingency and post-contingency states. Let $\mathcal{G}_n$ and $\mathcal{D}_n$ denote the sets of generators and loads connected to busbar $n$, respectively, $\mathcal{B}^F_n$ and $\mathcal{B}^T_n$ the sets of branches with from-end and to-end equal to $n$. The following constraints must be complied $\forall n \in \mathcal{N}$ and $c \geq 0$:

$$\sum_{g \in \mathcal{G}_n} P^c_{g,n} - \sum_{d \in \mathcal{D}_n} \left(P^c_{d,n} - P^{LS}_{d,n}\right) - \\ - \sum_{b \in \mathcal{B}^F_n} p^c_{b,s,n} - \sum_{b \in \mathcal{B}^T_n} p^c_{b,s,n} - (-1)^n \cdot p^c_k = 0 \tag{22}$$

### F. Topological Rules

Specific topological constraints are introduced to avoid ineffective switch combinations, based on the assumption that only one disconnector per side of a component can be closed on a busbar. Irrespective of whether the substation coupler $k$ is open or closed, it is numerically inconsistent to allow both disconnectors to remain closed simultaneously.

*1) Search space reduction constraints:* the solutions search space is significantly reduced if all elements in a substation $s$ are connected to busbar 1 when the coupler $k$ is closed, free to change busbar otherwise:

$$\sigma^s_k - 1 + \sigma_e \leq 0; \quad \forall s \in \mathcal{S}, e \in s \tag{23}$$

$$\sigma^s_k - 1 + \sigma_{b,i} \leq 0; \quad \forall s \in \mathcal{S}, \forall b \in s \tag{24}$$

$$\sigma^s_k - 1 + \sigma_{b,j} \leq 0; \quad \forall s \in \mathcal{S}, \forall b \in s \tag{25}$$

where $e$ in (23) denotes a single terminal component (generator or load), (24) and (25) are referred to branches.

*2) Loads & generators connection mode:* continuous variables are defined for generators ($P_{g,n}$) and loads ($P_{d,n}$), subject to the following restrictions:

$$P_{d,1} = p_d(1 - \sigma_d); \quad \forall d \in \mathcal{D} \tag{26}$$

$$P_{d,2} = p_d\sigma_d; \quad \forall d \in \mathcal{D} \tag{27}$$

$$0 \leq P^{LS}_{d,1} \leq p_d(1 - \sigma_d) \ \wedge \ 0 \leq P^{LS}_{d,2} \leq p_d\sigma_d; \forall d \in \mathcal{D} \tag{28}$$

$$P_{g,1} = p_g(1 - \sigma_g) \ \wedge \ P_{g,2} = p_g\sigma_g; \quad \forall g \in \mathcal{G} \setminus \{g^*\} \tag{29}$$

Denoting slack generators by $g^*$, (29) takes the following form, taking into account the technical limits $[\underline{p}_g, \overline{p}_g]$:

$$\underline{p}_g(1 - \sigma_g) \leq P_{g,1} \leq \overline{p}_g(1 - \sigma_g); \ \forall g = g^* \tag{30}$$

$$\underline{p}_g\sigma_g \leq P_{g,2} \leq \overline{p}_g\sigma_g; \quad \forall g = g^* \tag{31}$$

*3) Reliability Constraints:* Finally, these constraints help in ensuring N-1 security when a substation is and avoiding radially connected substations:

$$\sum_{b \in \mathcal{B}_s} \sigma_{b,s} \geq 2(1 - \sigma^s_k); \quad \forall s \in \{i, j\} \tag{32}$$

$$\sum_{b \in \mathcal{B}_s} [(1 - \sigma_{b,s}) - (1 - \sigma_b)] \geq 2(1 - \sigma^s_k); \quad \forall s \in \{i, j\} \tag{33}$$

$$\sum_{l \in \mathcal{L}_s} \sigma_l + |\mathcal{T}_s| \geq 2; \ \forall s \in \mathcal{S} \text{ if } \mathcal{G}_s = \mathcal{D}_s \neq \varnothing \wedge |\mathcal{B}_s| \geq 2 \tag{34}$$

In double-bus schemes, the number of connected branches to each busbar must be greater than or equal to 2, so that, if a line is tripped due to a contingency, there will be another path for this busbar to be connected to the grid [8].

The resulting optimization problem (2)-(34) is a big combinatorial MILP program with a pseudo-parallel structure due to contingency states and N-1 security constraints.

## III. Solution Methodology

Since solving the preventive SCOTNR can be particularly burdensome, an iterative C&CG algorithm is adopted to make the problem tractable and solvable in reasonable time. Furthermore, considering the extension of transmission systems, it is essential to perform preliminary screening procedures prior to optimization. Regarding contingencies selection, only transmission line contingencies that do not cause islanding, blackout, or uncontrollable overloads will be considered within the N-1 security constraints. This is because these cases are handled by specific procedures by the transmission system operator (TSO), being not manageable only with cost-free reconfiguration actions [12].

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### A. Iterative C&CG Solution Algorithm

The overall MILP problem is decomposed into a smaller MILP master problem (MP) and a set of $N_c$ independent LP slave problems (SPs) solved iteratively. These latter, are a continuous relaxation of the original MILP problem $\forall c > 0$, in which $\boldsymbol{u}_0 \in [0, 1]$. The MP determines an optimal topology in a pre-contingency state ($c = 0$), whereas each SP is a feasibility problem that checks the N-1 security ($\forall c > 0$). Note that the SPs can be solved sequentially or parallelized across multiple CPUs.

*1) Master Problem (MP):* the MP minimizes (2) subject to (4)-(22) with $c = 0$ and topological rules (23)-(34), giving a solution lower bound ($LB$). No contingency security constraints are included in the first step. The output is a combination of control variables $\hat{\boldsymbol{u}}_0$ to be submitted to the feasibility test carried out by the SPs.

*2) Slave Problems (SPs):* fixing the control variables $\boldsymbol{u}_0 = \hat{\boldsymbol{u}}_0$ derived from the MP, each SP minimizes the busbar power mismatch for each contingency state $c > 0$, where $\delta^+_{s,n,c}$ and $\delta^-_{s,n,c}$ are surplus and deficit active power mismatches on each busbar $n$ of substation $s$ due to contingency $c$, respectively.

$$\min_{\delta^+_{s,n,c},\ \delta^-_{s,n,c}} \Phi_c = \sum_{s\in\mathcal{S}} \sum_{n=1}^{2} (\delta^+_{s,n,c} + \delta^-_{s,n,c}); \quad \forall c > 0 \qquad (35)$$

subject to (4)-(21) and the following constraints:

$$\sum_{g\in\mathcal{G}_n} P^c_{g,n} - \sum_{d\in\mathcal{D}_n} \left(P^c_{d,n} - P^{LS}_{d,n}\right) - \sum_{b\in\mathcal{B}^F_n} p^c_{b,s,n} - \sum_{b\in\mathcal{B}^T_n} p^c_{b,s,n}$$
$$- (-1)^n \cdot p^c_k + \delta^+_{s,n,c} + \delta^-_{s,n,c} = 0, \quad \forall n \in \mathcal{N}, \forall c > 0 \quad (36)$$

where (35) quantifies the violations for each contingency state, (36) is the nodal active power balance taking into account slack quantities. From the SPs solution an upper bound ($UB$) can be derived by identifying the worst case contingency state.

*3) Potential Binding Contingencies:* The overall solution procedure is stated in Algorithm 1, where $\nu$ is the iteration counter and $\Omega^{(\nu)}_C$ the set of binding contingencies to be iteratively added to MP. Based on the conjecture of [13], $\Omega^{(\nu)}_C$ is updated in the iterative process only with the most binding contingencies, leading to a solution that is very close to the SCOTNR solution obtained by keeping them all. This iterative update acts as contingency filtering. Once convergence is achieved, the set $\Omega^{(\nu)}_C$ will contain only the contingencies strictly necessary to ensure compliance with the imposed N-1 security constraints, making the MP lighter.

It should be noted that the rows 6-9 of Algorithm 1 can be replaced with a static security assessment carried out with N-1 contingency analysis (CA) software tool, resulting in a co-simulation iterative procedure. Infeasibilities under N-1 states can be quickly checked by sorting and identifying the worst branch loading violations. The worst-case will be sent back to the MP as additional contingency case in the successive iterations.

**Algorithm 1** SCOTNR Iterative C&CG Solution Algorithm

1: Set $\nu \leftarrow 0$, $\epsilon \leftarrow 10^{-6}$, $\varepsilon \leftarrow 10^{-2}$, $\Omega^{(\nu)}_C \leftarrow \varnothing$
2: $LB^{(\nu)} \leftarrow -\infty$, $UB^{(\nu)} \leftarrow +\infty$
3: **while** $\nu \leq \nu^{max} \wedge (UB^{(\nu)} - LB^{(\nu)})/UB^{(\nu)} \geq \varepsilon$ **do**
4: $\quad\hat{\boldsymbol{u}}^{(\nu)}_0 \leftarrow$ solve $MP^{(\nu)}$
5: $\quad LB^{(\nu)} = f_0(\hat{\boldsymbol{u}}^{(\nu)}_0)$
6: $\quad$Fix $\boldsymbol{u}^{(\nu)}_c = \hat{\boldsymbol{u}}^{(\nu)}_0$
7: $\quad$**for** $c = 1, ..., N_c$ **do**
8: $\quad\quad\Phi^{(\nu)}_c \leftarrow$ solve $SP^{(\nu)}$
9: $\quad$**end for**
10: $\quad UB^{(\nu)} = \min\{UB^{(\nu-1)}, f_0(\boldsymbol{u}_0)^{(\nu)} + \max \Phi^{(\nu)}_c\}$
11: $\quad$**if** $\max \Phi^{(\nu)}_c > \epsilon$ **then**
12: $\quad\quad$update $\Omega^{(\nu)}_C \leftarrow \Omega^{(\nu-1)}_C \cup \arg\max_c(\Phi^{(\nu)}_c)$
13: $\quad$**end if**
14: $\quad\nu = \nu + 1$
15: **end while**

## IV. Test Results

Numerical experiments were carried out on modified IEEE 14-, 39- and 118-Bus test systems. Topological arrangements were made to represent double-bus single breaker substations, resulting in three new different benchmark systems for reconfiguration studies. The preventive SCOTNR problem is solved by considering different objective functions, such as economic dispatch (ED), topological operations (TOs)–line switching (LSOs), substation splitting (SSOs), PST operations (PSTOs)– and load shedding (LS). In the initial operating condition, all the electrical components are connected to busbar 1 within substation. All line loadings must be within 100% and 120% under N and N-1 conditions, respectively.

### A. 14 Double-Bus System

The first benchmark system has the same features of the network used in [8], involving 13 substations for a total of 26 busbars. A 3-winding transformer is connected to substations #4, #8 and #9. In the initial operating condition, line #4 (2-3) is congested at 102.06%. The SCOTNR results are summarized in Table I.

TABLE I
SCOTNR Results For 14 Double-Bus System

| | ED+LS | ED+TOs | TOs+LS | ED+TOs+LS |
|---|---|---|---|---|
| $f_0$ [p.u.] | 2.3116 | 0.3318 | 0.5774 | 0.3318 |
| Gen. costs [$/h] | 4957.36 | 3268.00 | 4874.40 | 3268.00 |
| LS costs [$/h] | 18159.00 | | 0 | 0 |
| LSOs [-] | | 0 | 0 | 0 |
| SSOs [-] | | 0.005 | 0.005 | 0.005 |
| PSTOs [-] | | 0 | 0.085 | 0 |
| CPU time [s] | 0.12 | 2.13 | 4.64 | 1.43 |

The same solutions are obtained also with Algorithm 1 with low CPU times considering 16 line contingencies. The same solution described in [8] was obtained in the ED+TOs+LS case. When reconfiguration is not considered (ED+LS), 1.82 MW of the load should be curtailed, whereas PSTs help in avoiding LS when only cost-free actions are allowed (TOs+LS).

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### B. 39 Double-Bus System

In this test system with 39 substations (70 busbars), line #26 is congested at 101.46%. 34 contingencies are considered within the SCOTNR. As stated in Table II, a N-1 secure configuration cannot be obtained only with TOs+LS. In the ED+LS case, 3.72 MW of load are curtailed and the system costs increase due to generation dispatch. Conversely, switching off line #5 allow to achieve an optimal solution while less generation needs to be redispatched compared to ED+LS case.

TABLE II
SCOTNR RESULTS FOR 39 DOUBLE-BUS SYSTEM

| | ED+LS | ED+TOs | TOs+LS | ED+TOs+LS |
|---|---|---|---|---|
| **$f_0$ [p.u.]** | 17.4861 | 13.6945 | infeasible | 13.6945 |
| **Gen. costs [\$/h]** | 137706.35 | 136895.45 | 153683.39 | 136895.45 |
| **LS costs [\$/h]** | 37154.48 | | infeasible | 0 |
| **LSOs [-]** | | 0.005 | infeasible | 0.005 |
| **SSOs [-]** | | 0 | infeasible | 0 |
| **PSTOs [-]** | | 0 | infeasible | 0 |
| **CPU time [s]** | 0.42 | 47.81 | n/a | 47.96 |

### C. 118 Double-Bus System

In this study case, line #161 is 107.05% overloaded. Results (Table III) are obtained considering 166 line contingencies. Overall, the SCOTNR problem applied to this test case includes 1,268,367 constraints, 336,811 continuous variables, and 837 integer variables (of which 809 are binary).

TABLE III
SCOTNR RESULTS FOR 118 DOUBLE-BUS SYSTEM

| | ED+LS | ED+TOs+LS | ED+PSTOs |
|---|---|---|---|
| **$f_0$ [p.u.]** | 9.8526 | 9.8206 | 11.1287 |
| **Gen. costs [\$/h]** | 98526.25 | 98105.61 | 10893.69 |
| **LS costs [\$/h]** | 0 | 0 | 0 |
| **LSO [-]** | | 0 | 0 |
| **SSO [-]** | | 0.01 | 0 |
| **PSTO [-]** | | 0 | 0.235 |

Additional tests were carried out considering 100% as the maximum line loadings in N-1 conditions. Given its size, the SCOTNR problem cannot be solved within 1 hour without the use of Algorithm 1 when TOs are allowed, except for the case in which only PSTs with ED are enabled. This case solved with the full MILP formulation took only 23.24 s and the grid can be considered N-1 secure.

### D. Software Tools & Computational Performances

All numerical simulations were performed in a Python environment on a computer with 32 GB RAM, 12th Gen Intel® Core™ i9-12900F CPU @ 2.40 GHz, 16 physical cores and 24 logical processors, using up to 24 threads. DIgSILENT PowerFactory is used to represent the grid and to perform DCLF and N-1 CA calculations. The MILP optimization framework is built within *Pyomo* library using Gurobi 12.0, which uses Branch&Bound and Primal-Dual Simplex algorithms to solve the MILP problem. A CPU time comparison for 118 Double-Bus is shown in Table IV, showcasing improvements with the co-simulation approach.

TABLE IV
CPU TIMES FOR 118 DOUBLE-BUS SYSTEM [S]

| | ED+LS | ED+TOs | ED+TOs+LS |
|---|---|---|---|
| **Full MILP [s]** | 4.93 | $> 3600$ | $> 3600$ |
| **C&CG (MP/SPs) [s]** | 18.59 | 51.89 | 53.85 |
| **C&CG (co-simulation) [s]** | 6.96 | 6.37 | 6.52 |

## V. CONCLUSION

This work addressed the challenge of solving a deterministic preventive N-1 SCOTNR problem on three different size benchmark systems. The adoption of a MILP formulation proved useful for identifying switching operations for N-1 security constrained CM purposes. The C&CG iterative solution algorithm was essential for the problem tractability on 118 Double-Bus System. Test results showed that topological changes combined with redispatch allow to ensure system security with lower operation costs. In certain cases, topological operations were proved to be essential to avoid load shedding and reduce system costs as well. The proposed approach allowed to reach a solution even considering a very large set of contingencies (166) on 118 Double-Bus System. Future developments will consist of exploring a possible deterministic methodology to address the AC SCOTNR problem, integrating the switching decisions with the other voltage controls that can be managed by the TSO.

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