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Risk-based approach to the Optimal Transmission Switching problem

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***Abstract*—This paper deals with the secure Optimal Transmission Switching (OTS) problem in situations where the TSO is forced to accept the risk that some contingencies may result in the de-energization of parts of the grid to avoid the violation of operational limits. This operational policy, which mainly applies to subtransmission systems, is first discussed. Then, a model of that policy is proposed that complements the classical MILP model of the N-1 secure OTS problem. It comprises a connectivity and notably a partial grid loss analysis for branch outage contingencies. Finally, its application to the IEEE 14-bus system is presented. Solutions similar to those observed in operation are reached by the algorithm, notably revealing the preventive-openings-cascade phenomenon.**

***Index Terms*—transmission network, reconfiguration, topology, switching, risk, connectedness**

NOMENCLATURE

We consider a graph $\mathcal{G}$ and denote vectors in lowercase bold $\boldsymbol{u}$, and matrices in uppercase bold $\boldsymbol{A}$.

Functions and operators

$\odot$	Hadamard product: elementwise multiplication
$\langle.,.\rangle$	Inner product
$\delta_{c,i}$	Kronecker function: 1 if $c = i$; 0 otherwise
$\mathrm{org}(e)$	Origin vertex index of edge e
$\mathrm{dst}(e)$	Destination vertex index of edge e
$\mathrm{inc}(i)$	Incident edges of vertex i
$\mathrm{opp}(e,i)$	For an edge e connected to a vertex v, the vertex on the other end of e, distinct from v.

For example, if $e \in \mathrm{inc}(v)$, then v is either in $\mathrm{org}(e)$ or $\mathrm{dst}(e)$. Moreover, if $v = \mathrm{org}(e)$, then $v = \mathrm{opp}(e, \mathrm{dst}(e))$.

Sets

$\mathcal{V}$	indices of the vertices or buses of $\mathcal{G}$
$\mathcal{E}$	indices of the edges or branches of $\mathcal{G}$
$\mathcal{C}^\star$	edge indices of contingencies, $\mathcal{C}^* \subset \mathcal{E}$.
$\mathcal{C}$	edge indices of contingencies including 0 for none

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Matrices, vectors and scalar

$\boldsymbol{A}$	The incidence matrix of $\mathcal{G}$. $\boldsymbol{A}_{ve} = 0$ if the edge e does not connect the vertex v, 1 if it is oriented toward v; -1 otherwise.
$\boldsymbol{0}, \boldsymbol{1}$	vectors filled respectively with 0 and 1
$\boldsymbol{g},\ \boldsymbol{d}$	Generations, loads on buses
$\boldsymbol{p}$	$\boldsymbol{p} = \boldsymbol{g} - \boldsymbol{d}$ Net injections on buses
$\boldsymbol{b}$	Susceptances of branches
$\bar{\boldsymbol{f}}$	Flow limits on branches
$\boldsymbol{v}$	Binary vector indicating branch openings in the base case. $v_e = 1$ if edge e is open, 0 otherwise

For a contingency $c \in \mathcal{C}$:

$\hat{\boldsymbol{g}}_c,\ \hat{\boldsymbol{d}}_c$	Post-contingency generations and loads
$\boldsymbol{f}_c$	Directed flows in the edges
$\boldsymbol{\phi}_c$	Voltage phase angles in the buses
$\boldsymbol{p}^\star_c$	Net injections in N-1 mirror graph
$\boldsymbol{f}^\star_c$	Flows in N-1 mirror graph
$\boldsymbol{w}_c$	Binary vector indicating that the branch is opened either in the base case ($\boldsymbol{v}$) or because of the contingency c
$\mathfrak{p}_c$	Probability of occurrence of contingency c
$\boldsymbol{\pi}_c$	Binary vector indicating the energized status of buses. $\boldsymbol{\pi}_{c,i} = 1$ if bus i is energized, 0 else
$\psi_{c,i,e}$	Variable indicating whether the bus connected to bus i via edge e is energized
σ_c	Generation scaling factor

I. INTRODUCTION

One of the primary concerns of Transmission System Operators (TSOs) is ensuring the security of the power system. To achieve this, they must anticipate potential events that can compromise it while simultaneously striving to maintain economic efficiency. When it comes to security policies, the cornerstone is the N-1 rule. Sometimes, it is reduced to the statement that the consequences of the tripping of any single element of the grid shall have no impact on the users of the power system. This is actually a narrow view. In fact, the rule derives from a risk-based principle. As contingencies are likely to occur, what is at stake for the operator is that any resulting state of the system remains under control. In other words, the consequences of any likely tripping of a branch shall be mastered. Furthermore, to align the risks to the same level, the more likely a contingency is, the less acceptable its consequences in case of occurrence. So, the criteria the operator follows are based on the definition of the limits between an acceptable and an unacceptable consequence with respect to each contingency considered.

Keeping flows or voltages within security limits is one of the key criteria. Losing a part of the grid and de-energizing users could also be considered unacceptable, but is it realistic? In fact, enforcing the latter constraint implies that the real-time operator must avoid *at all costs* losing customers as a result of a single tripping. This may involve operations on the grid itself, for example, by implementing switching actions or activating redispatch or curtailment of customers, which rapidly becomes expensive.

EU regulation [1] does not contain such standards. *Loss* is only explicitly mentioned in the description of the security states where it is introduced for the black-out state, which is defined by the *loss* of more than 50% of the total consumption of the control area of the TSO. The fact that there is no specific standard reflects at least that there is no requirement to not lose any part of the grid, and opens to the interpretation that the regulation admits this may happen. Moreover, there may be operational scenarios where solutions that avoid all customer disconnections do not exist.

This paper considers situations where no solution is available, or where the costs associated with the mitigation of potential loss of parts of the grid are prohibitive. Such cases are addressed in the context of the Optimal Transmission Switching (OTS) problem.

The OTS problem consists in finding the combination of branch openings in the grid that optimizes a given objective function. Many optimization approaches to the OTS problem have been developed. [2] by Fisher *et al.* is the first DC-OPF (Direct Current Optimal Power Flow) based on an MILP (Mixed-Integer Linear Program) approach to it with the goal of solving *congestion*. This pioneering study lays the foundation for numerous subsequent efforts that employ the DC approximation to solve the OTS. In this model, the switching problem is formulated using a big-M approach and the necessary flexibility – when no switching scheme is enough to cope with the congestion – is provided by the OPF equations that aim at minimizing generation adjustment cost. Hedman *et al.* extended that approach in [3] to include *security analysis* and incorporate the N-1 rule. The algorithm does not permit the loss of load or generation, but it does allow electrical islands either in the base case or after a contingency if the resulting islands satisfy all the constraints. In practical operation, islanding should only be considered in very particular power systems that are designed to be sustainable after a grid split, which implies the fulfillment of a lot of requirements in terms of balancing, control, and stability. To avoid islanding, various recent papers therefore take into account a connectivity constraint, for which various approaches have been proposed ([4], [5], [6], [7]).

The contribution of this article is threefold. First, a discussion of the N-1 rule is presented and consequences of including it in operation are presented. Then a deterministic optimization model that reflects that risk-based operational policy is developed. At its core, the connectedness of the network in the base case and in the N-1 situations is assessed. Finally, its application to the IEEE 14-bus system is analyzed.

II. A risk-based approach to the OTS

A. Grid designs and security

The authors of [8] expose various designs of power grids and analyze the implications in terms of security level. Underlying their rationale is the principle that the lower the consequences, the more acceptable they are. By applying that logic, the distribution systems are operated radially, though such an operating scheme puts all the connected users under the risk of being shut down by the contingency of any element of the string of elements connecting it to the source substation. In contrast, transmission systems dealing with larger areas are exposed to bigger consequences and foster a meshed operation to secure each substation. Therefore, the bulk transmission grid is operated fully meshed, whereas underneath, subtransmission parts are operated looped or meshed, some parts being operated as pocket under one single feeding point, or groups connected to multiple feeding points.

These parts of the transmission grid are more prone to being operated with insecure areas. This is especially the case where the grid is weakly developed, or if the development could not follow the settlement of grid users, during maintenance periods that require outages of nonredundant elements, or following a contingency. One must accept that some areas of the system – even if internally meshed – would only be connected to the main part of the network through a single branch. In that case, should this branch trip, the whole area is de-energized.

But that insecurity does not mean that the transmission system operator lacks control. The consequences of each potential contingency must be clearly identified and mastered. No tripping should result in violation of physical limits, cascading effects, or grid collapses. Should a given contingency lead to loss of a part of the system with loads and/or generations, the extent of the consequences must be assessed *a priori* and weighted against its probability of occurrence.

B. Implication to the transmission switching design process

This aspect of policy must be considered by operators when designing their operational strategies and especially when designing the switching patterns. Whereas for some assets, the possibility of temporarily overloading a branch may pose acceptable risks, this may not be the case for other assets. We consider the latter case, where even if the probability is low, the consequence is considered unacceptable as this could destroy assets or worse still expose people around to potentially fatal outcomes.

Consider the case of a subtransmission area connected to the bulk grid through two branches. Should the tripping of either one lead to overloading of the other, the operator must take preventive actions. One option consists in involving grid

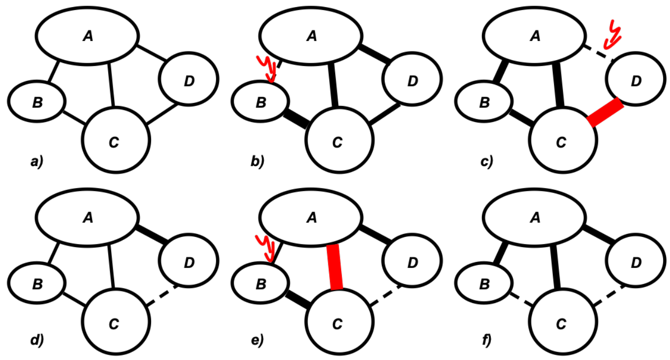


Fig. 1: Preventive-openings-cascade. Each bubble represents a portion of a grid a) the initial pattern; b) after the tripping of AB, no overloading and B is secured; c) the preventive opening of CD; d) the tripping of AB now leads to an overloading of AC; e) the tripping of AD results in an overloading on CD which implies the opening of BC f) final situation avoiding post-contingency overloadings.

users in the area and requesting a change in their injections, which is costly and would need to be done irrespective of whether the contingency occurs. The other consists in splitting the area into two disconnected pockets, each hanging on one branch. Now, if a tripping occurs on one of these branches, the corresponding pocket is lost, but there would be no forbidden overloading. That is an application of the security/cost trade-off: to decide between spending money for redispatching and ensuring security or taking the risk of losing an area, which would be very unlikely, but with potential significantly higher costs. In the latter case, this may imply the search for an optimum among all the possibilities of splitting the area into two pockets. This is the focus of this paper.

The next illustration pushes a similar rationale in a more complex context and highlights the preventive-openings-cascade phenomenon. Figure 1 shows the chain of implications of taking into account the consequence of contingencies. An opening that weakens its neighboring area requires another opening. Repeating this rationale results in a topology scheme with separated pockets, each one hanging on a single branch. It is worth noting that the grid may be meshed within pockets, so that inner trippings do not necessarily result in de-energizations.

C. Application to the OTS

The OTS aims to find an optimal solution that aligns with the risk-based principle underlying the N-1 rule. It therefore is necessary to integrate the following conditions:

- there must be no overloading in the base case;
- the risk associated with the tripping of a single branch is considered too high, if it leads to overloading, therefore, there must be no overloading after any tripping of a single branch;
- if no other option is available, or if the cost of mitigating exposure is prohibitively high, certain parts of the grid may face the risk of being de-energized as a result of the tripping of a single branch;
- the risk of being de-energized must be minimized by applying the switching schemes that limit as much as possible the exposure to that risk.

III. MILP MODELING

A. Principles

This section develops an MILP formulation of the approach described above. The aim is to determine preventive branch openings, if any, that will optimally reduce system risk. These are described by a binary vector $\boldsymbol{v}$, indicating the pre-contingency status of each branch (1 is open).

The base case is supposed to be balanced and the model shall ensure its connectedness (III-B). On the other hand, in N-1 the connectedness is assessed to identify for each contingency which part of the grid, if any, is de-energized (III-C). The generators remaining in the energized area are adjusted to ensure the balance of the N-1 case (III-D). Finally, a secured DC power flow (III-E) is modeled to assess the flows in the branches, and constraints are added to include their flow limitations. The cost function aiming at minimizing the risk taken is described in III-F.

Some formulations are not directly applicable as MILP for they involve logical operations or Hadamard product of variables. They are first exposed in their concise form for simplicity and readability, and the steps used to translate them into MILP formulations are given in III-G.

B. Base case connectedness

In order to ensure the connectedness of the grid in the base case, (1) implements a method inspired by [5] involving a fictitious mirror graph. A subscript 0 is used to indicate the pre-contingency base case.

$$\boldsymbol{f}_0^\star \odot \boldsymbol{v} = 0 \tag{1a}$$
$$\boldsymbol{A}\boldsymbol{f}_0^\star = \boldsymbol{p}_0^\star \tag{1b}$$
$$p_{0,i}^\star = 1 \qquad \forall i \in \mathcal{V}\backslash\{s\} \tag{1c}$$
$$p_{0,s}^\star = -(|\mathcal{V}| - 1) \tag{1d}$$

The mirror graph has the same vertices and edges as the graph of the grid. If one branch is open in the grid, the corresponding edge is open in the mirror graph, and its flow is null (1a). In this mirror graph, the only law that applies is the principle of conservation (1b). One vertex with the index s is chosen as the source – a virtual generator. All others consume 1 (1c). Thus, if the graph is connected, there is a connected path between the source vertex and any of the others, and by application of the principle of conservation, the source vertex shall produce $|\mathcal{V}| - 1$, which is ensured by (1d). Only a connected graph can satisfy these constraints.

C. N-1 Connectedness handling

We consider only branch opening contingencies; hence we use the convention that contingency $c \in \mathcal{C}^*$ corresponds to opening of branch c. A new binary vector $\boldsymbol{w_c}$ is introduced that combines the switching status of the branches for the contingency c. $w_{c,e}$ has value 1 if the edge e is open either preventively by the OTS or because of the contingency; it is 0 otherwise:

$$w_{c,e} = v_e \vee \delta_{c,e} \qquad \forall\, (c,e) \in \mathcal{C} \times \mathcal{V} \tag{2}$$

Note that for index $c = 0$ (the base case), $\boldsymbol{w}_0 = \boldsymbol{v}$.

In the risk-based approach, after a contingency, part of the grid may be deenergized. As for the base case connectedness, a fictitious mirror graph is implemented (3) for each considered contingency in $\mathcal{C}$. However, the goal is no longer to ensure connectedness, but rather to identify the buses that would be disconnected from the Main Connected Component (MCC) of the grid after the trip. The MCC is defined as the set of nodes connected to the mirror grid source vertex. For simplicity, the same vertex s chosen for the base case is used here, but more elaborate definitions could be used, including the use of a contingency-specific source vertex.

$\forall c \in \mathcal{C}^*$:

$$\boldsymbol{f}_c^\star \odot \boldsymbol{w}_c = \boldsymbol{0} \tag{3a}$$
$$\boldsymbol{A}\boldsymbol{f}_c^\star = \boldsymbol{p}_c^\star \tag{3b}$$
$$\pi_{c,i} \in \{0,1\} \qquad \forall i \in \mathcal{V} \tag{3c}$$
$$\pi_{c,s} = 1 \tag{3d}$$
$$p_{c,s}^\star \in \{-(|\mathcal{V}|-1), ..., 0\} \tag{3e}$$
$$p_{c,i}^\star = \pi_{c,i} \qquad \forall i \in \mathcal{V}\backslash\{s\} \tag{3f}$$
$$\pi_{c,i} = \bigvee_{e \in \mathrm{inc}(i)} \left[\pi_{c,\mathrm{opp}(i,e)} \wedge (1 - w_{c,e})\right] \qquad \forall i \in \mathcal{V} \tag{3g}$$

Equations (3a) and (3b) play the same role as (1a) and (1b). To identify the part of the grid that remains in the main connected component, an indicator variable $\pi_{c,i}$ is introduced that is set to 1 for the contingency c if the vertex i is energized (3c), 0 otherwise. Its value for the source vertex is set to 1 as it is per definition in the MCC (3d). Now, a similar approach to that of the base case is applied where the source vertex s is the only one that generates connectedness flow (3e), and all the other vertices consume it with a value of $\pi_{c,i}$ (3f). So, when the vertex i is not connected to the MCC, as there is no connected path to the source vertex, the vertex cannot consume and $\pi_{c,i} = 0$. In fact, having $p_{c,i}^\star = 1$ would contradict 3b in the de-energized area. This only ensures that $\pi_{c,i}$ is set to 0 for de-energized buses. The next mechanism is necessary to force it to be 1 in the energized area. Starting from the source vertex for which $\pi_{c,s} = 1$, the status propagates by (3g). Each bus i must be energized if at least one of its connected ($w_{c,e} = 0$) neighbors is also energized.

D. Balancing the energized area

If a tripping leads to a de-energized area ($\pi_{c,i} = 0$), then the generation and load in the remaining nodes must be balanced to continue operation. We choose to balance by shifting all remaining energized generators proportionally to their initial values:

$\forall c \in \mathcal{C}^*$:

$$\hat{\boldsymbol{d}}_c = \boldsymbol{d} \odot \boldsymbol{\pi}_c \tag{4a}$$
$$\hat{\boldsymbol{g}}_c = \sigma_c \boldsymbol{g} \odot \boldsymbol{\pi}_c \tag{4b}$$
$$\langle \boldsymbol{1}, \hat{\boldsymbol{g}}_c - \hat{\boldsymbol{d}}_c \rangle = 0 \tag{4c}$$

$\hat{\boldsymbol{g}}_{\boldsymbol{c}}$ and $\hat{\boldsymbol{d}}_{\boldsymbol{c}}$ represent the adjusted values of the generation and load after contingency. (4a) sets the load to 0 when the substation is de-energized and to its initial value otherwise. Similarly, (4b) applies to generation, including the generation scaling factor σ_c that ensures that the system is balanced (4c). As power adjustments are relatively small ($\sigma_c \approx 1$), generator limits are not explicitly modeled.

E. Flows

With the base case holding the index $c = 0$ and having $\hat{\boldsymbol{d}}_0 = \boldsymbol{d}$ and $\hat{\boldsymbol{g}}_0 = \boldsymbol{g}$, the flows in the grid are calculated for all cases using the classical DC power flow formulation (5). An AC formulation is obtained by making the relevant substitutions from DC to AC power flow, but this will naturally prevent its expression as a MILP.

$\forall c \in \mathcal{C}$:

$$\boldsymbol{f}_c \odot \boldsymbol{w}_c = \boldsymbol{0} \tag{5a}$$
$$f_{c,e} = b_e \left(\phi_{c,\mathrm{dst}(e)} - \phi_{c,\mathrm{org}(e)}\right) \odot (1 - w_{c,e}) \quad \forall e \in \mathcal{E} \tag{5b}$$
$$\boldsymbol{A}\boldsymbol{f}_c = \hat{\boldsymbol{g}}_c - \hat{\boldsymbol{d}}_c \tag{5c}$$
$$|\boldsymbol{f}_c| \preceq \overline{\boldsymbol{f}} \tag{5d}$$

When a branch is open, its flow shall be null (5a). The flow in the branch e results from the phase angle difference between its buses (5b) when the branch is closed. (5c) expresses the power balance in the buses (and implies (4c)). Finally, (5d) limits the flows in the branches to their respective operational limits.

F. Cost function

The cost function to be minimized (6) consists of the risk due to de-energized nodes. We define the risk of a single contingency c as its probability $\mathfrak{p}_c$ of occurrence during the relevant operating window, multiplied by the volume of the consequent load loss $\langle 1, \boldsymbol{d} - \hat{\boldsymbol{d}}_c \rangle$. Other definitions of the risk, for example, also involving the duration or costs of loss of generation, could be considered.

$$\min_{\boldsymbol{v}} \sum_{c \in \mathcal{C}^\star} \mathfrak{p}_c \langle 1, \boldsymbol{d} - \hat{\boldsymbol{d}}_c \rangle \tag{6}$$

The risk-based OTS problem minimizes the sum of contingency risks for the chosen switch configuration $\boldsymbol{v}$.

G. Big-M formulation

Some equations are not pure MILP operations. This subsection gathers a reformulation of them for an MILP solver using the big-M technique, where M is a sufficiently large scalar.

The equations involving Hadamard products of variables in the formulation (1a), (3a), (4b) and (5a), generalize under the form $\boldsymbol{a} = k\boldsymbol{b} \odot \boldsymbol{u}$, with k a scalar and $\boldsymbol{u}$ an indicator vector and $\boldsymbol{a}$ and $\boldsymbol{b}$ vectors of reals. It translates as follows:

$$\boldsymbol{a} \preceq M\boldsymbol{u} \tag{7a}$$
$$-\boldsymbol{a} \preceq M\boldsymbol{u} \tag{7b}$$
$$\boldsymbol{a} - k\boldsymbol{b} \preceq M(\boldsymbol{1} - \boldsymbol{u}) \tag{7c}$$
$$-\boldsymbol{a} + k\boldsymbol{b} \preceq M(\boldsymbol{1} - \boldsymbol{u}) \tag{7d}$$

The absolute value in (5d) translates in

$$\boldsymbol{f}_c \preceq \overline{\boldsymbol{f}} \tag{8a}$$
$$\boldsymbol{f}_c \preceq -\overline{\boldsymbol{f}} \tag{8b}$$

The last equation to be adapted is the logical expression (3g). To do so, the following translation of the logical operators on binary variables will be necessary:

$$x = a \vee b \Leftrightarrow \begin{cases} x \geq a \\ x \geq b \\ x \leq a + b \end{cases} \tag{9a}$$

$$x = a \wedge b \Leftrightarrow \begin{cases} x \leq a \\ x \leq b \\ x \geq a + b - 1 \end{cases} \tag{9b}$$

First, we introduce an intermediate binary variable $\psi_{c,i,e}$ which is defined $\forall c \in \mathcal{C}, \forall i \in \mathcal{V}, \forall e \in \text{inc}(i)$

$$\psi_{c,i,e} = \pi_{c,\text{opp}(i,e)} \wedge (1 - w_{c,e}) \tag{10}$$

which translates using (9), into

$$\psi_{c,i,e} \leq \pi_{c,\text{opp}(i,e)} \tag{11a}$$
$$\psi_{c,i,e} \leq 1 - w_{c,e} \tag{11b}$$
$$\psi_{c,i,e} \geq \pi_{c,\text{opp}(i,e)} - w_{c,e} \tag{11c}$$

Now (3g) becomes

$$\pi_{c,i} = \bigvee_{e \in \text{inc}(i)} \psi_{c,i,e} \quad \forall (c,i) \in \mathcal{C} \times \mathcal{V} \tag{12}$$

which translates using (9) into
$\forall (c,i) \in \mathcal{C} \times \mathcal{V}$:

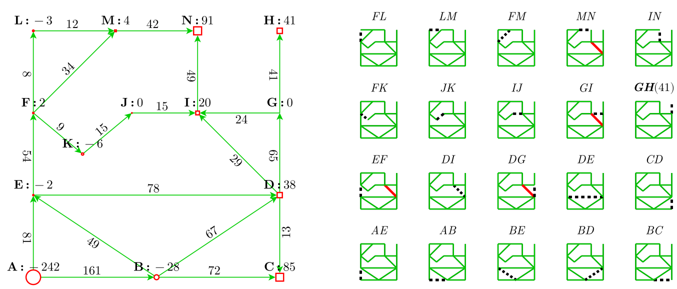
$$\pi_{c,i} \leq \sum_{e \in \text{inc}(i)} \psi_{c,i,e} \tag{13a}$$
$$\pi_{c,i} \geq \psi_{c,i,e} \qquad \forall e \in \text{inc}(i) \tag{13b}$$

IV. Results

The model was applied to the IEEE 14-bus network and a single loading scenario, shown in Fig. 2. The contingency list contained all branches, that is, $\mathcal{C} = \mathcal{E}$, and for this initial study all contingencies were assumed to be equally likely. It was modeled in Julia and solved by Gurobi 11 on an Apple M3. The computation time was 1.8 seconds, which in Gurobi's metric corresponds to 3.26 work units.

Figs. 2-4 each consist of two panels. The pre-contingency scenario is shown on the left. Buses represented as circles are generating, while those represented as squares are consuming. Their sizes follow the absolute value of their injections, and net consumption (in MW) is given. Branches are color coded as black (opened by the OTS algorithm) or green (closed), where arrows and numbers indicate the flow (in MW).

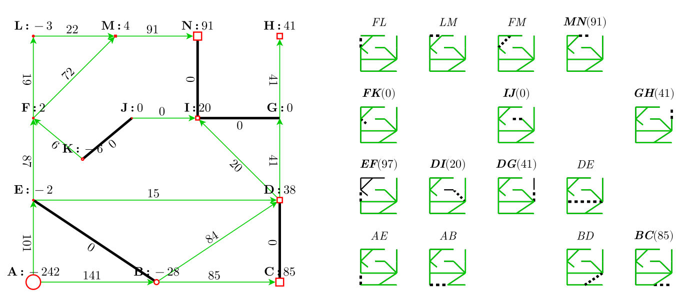
The security analysis is shown on the right of each figure. The title of each subfigure is the name of the branch that tripped. It is in bold style when a part of the grid is de-energized and the load lost is in brackets. In the security analysis figures, the lines opened by the OTS algorithm are removed, dashed black lines are those the contingency one, and solid black lines those that are in a de-energized area. The already opened lines are removed and overloaded lines are shown in red.



(a) base case (b) security analysis

Fig. 2: Base without OTS: There is no overflow in the base case. The security analysis reveals that numerous trippings raise an overloading on ID.

The base case is shown in Figure 2a. There is no overloading; therefore, if branches are to be open, it is only to cope with overloads in N-1. The source vertex corresponds to the bus A, which holds the largest generator. Figure 2b shows the results of the security analysis where 4 of 20 trippings end with the overloading of the branch DI. As GH forms an antenna, its tripping results in the loss of the bus H.



(a) base case (b) security analysis

Fig. 3: Base case with OTS.

Figure 3a shows the situation with the branch opening proposed by our algorithm. As expected, there is no overloading anymore as shown by the security analysis in Figure 3b, but this comes at the cost of loss of buses for for 8 of 14 contingencies. Now, DI only holds an antenna with the load of the buses I and J and its load will never exceed the sum of both consumptions. However, to isolate this antenna, IG is opened, which grows the previously existing antenna with

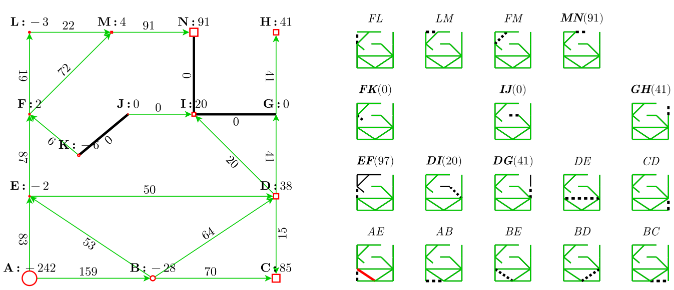
TABLE I: Result summary

metric	Scenario		
	base	***intermediate***	***optimized***
preventive branch openings	0	3	5
contingencies with overloads	4	1	0
contingencies with de-energized buses	n/a[a]	n/a[a]	8
average demand loss, per contingency	n/a[a]	n/a[a]	6.7%

[a]due to overloads, consequences are unknown.

G and H. In addition, IN and IJ are opened, creating a peninsula held on branch EF with the buses F, K, L, M and N.

That scenario also reveals the preventive-openings-cascade phenomenon. In fact, in the base case, only the branch DI is at risk of being overloaded and the opening of JK, IN and GI may appear at first sufficient. Figure 4 shows the intermediate state if the operator only focuses on the initial constraint. None of the trippings in the northern area leads to overloads. But that reconfiguration also affected the distribution of the flows in the southern part, which raises a new constraint. Now, the tripping of AE, which was previously sound, ends with the overloading of the branch BE. Thus, resolving the constraint in the northern area weakens the southern one, and consequently a reconfiguration becomes also necessary in that area: the opening of the branches BE, and CD, and now BC becomes an antenna.



(a) base case (b) security analysis

Fig. 4: Intermediate case the operator would needed to step into. The branch openings in the northern area solve the constraint on branch DI, but raises one on branch BE.

This rationale is similar to what would have been necessary for an operator facing the same situation. Sometimes back and forth steps are necessary. This kind of iterative approach is time consuming even for such a simple case, and the operator would settle for a solution that respects the security rules, even if it may be far from optimal. Thanks to the optimization technique, all the constraints are incorporated into one single problem and then solved at once. Moreover, by taking into account the probability associated with the tripping of each individual line, as well as the subsequent loss, a solution can be found that completely avoids the exposure to the unknown risks associated with overloading and minimizes the risk related to de-energized buses. The performance is summarized in Table I.

V. Conclusion

Noting that the N-1 rule is fundamentally a risk-based approach, our approach highlights situations that necessarily happen in transmission grids, and especially in subtransmission systems where the risk of de-energizing parts of the grid following a single contingency is considered. This operational policy is modeled as an MILP, which leverages connectivity analysis in the N-1 cases that is incorporated into the OTS problem. As a result, solutions similar to those observed in operation are reached by the algorithm, notably revealing the preventive-openings-cascade phenomenon. The application of such an approach would benefit the operator, as the design of these strategies is time consuming.

In future work, this approach will be extended with bus splitting actions that are generally preferred to line openings, AC power flow to take into account reactive power and voltage limitations, and completed with an Optimal Power Flow to include the redispatching lever. Finally, the algorithm must scale for solving the problem on real-size grids.

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References

[1] Council of European Union, “Commission regulation (eu) 2017/1485 of 2 august 2017 establishing a guideline on electricity transmission system operation,” 2017, 2025-01-10. [Online]. Available: https://op.europa.eu/fr/publication-detail/-/publication/d09a428c-8957-11e7-b5c6-01aa75ed71a1/language-en

[2] E. Fisher, R. O’Neill, and M. Ferris, “Optimal Transmission Switching,” *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1346–1355, 2008, 10.1109/TPWRS.2008.922256.

[3] K. Hedman, R. O’Neill, E. Fisher, and S. Oren, “Optimal Transmission Switching With Contingency Analysis,” *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1577–1586, Aug. 2009, 10.1109/TPWRS.2009.2020530.

[4] J. Ostrowski, J. Wang, and C. Liu, “Transmission Switching With Connectivity-Ensuring Constraints,” *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 2621–2627, 2014, 10.1109/TPWRS.2014.2315434.

[5] T. Ding, K. Sun, C. Huang, Z. Bie, and F. Li, “Mixed-Integer Linear Programming-Based Splitting Strategies for Power System Islanding Operation Considering Network Connectivity,” *IEEE Systems Journal*, vol. 12, no. 1, pp. 350–359, Mar. 2018.

[6] T. Han, Y. Song, and D. J. Hill, “Ensuring Network Connectedness in Optimal Transmission Switching Problems,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 68, no. 7, pp. 2603–2607, 2021, 10.1109/TCSII.2021.3059070.

[7] P. Li, X. Huang, J. Qi, H. Wei, and X. Bai, “A Connectivity Constrained MILP Model for Optimal Transmission Switching,” *IEEE Transactions on Power Systems*, vol. 36, no. 5, pp. 4820–4823, 2021, 10.1109/TPWRS.2021.3089029.

[8] M. N. Eggleton, E. Van Geert, W. L. Kling, M. Mazzoni, and M. A. M. M. Van Der Meijden, “Network structure in sub-transmission systems. Features and practices in different countries.” *2th International Conference on Electricity Distribution, 1993. CIRED, Birmingham, UK*, vol. 6, pp. 6.9/1–6.9/8, 1993.