Transformer Protection in Large-Scale Power Systems During Geomagnetic Disturbances Using Line Switching

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***Abstract*—Geomagnetically induced currents (GICs) can increase the reactive power loss in transformers and potentially cause permanent damage due to overheating. This paper considers line switching as a remedial action to protect transformers from geomagnetic disturbances. The algorithm uses linear sensitivity analysis to find an effective switching strategy, which minimizes the number of opened lines subject to satisfying the transformer thermal limits. To reduce the computational complexity for large-scale power systems, the critical lines are identified through sensitivity analysis and the optimization is performed on the reduced system. Furthermore, the effect of GICs on the ac power flow solution is modeled and heuristic techniques are developed to provide sufficient security measures in terms of both GIC flows and ac analysis. Finally, a multiaction solution with an alternating schedule is developed for severe storms when the losses are significant and a single switching action cannot remove the stress from all transformers at a time. The actions are obtained through a recursive algorithm, which divides the original problem into smaller subproblems with fewer constraints and solves them recursively. The effectiveness of the proposed algorithm is demonstrated through numerical results using a 150-bus and a 2000-bus system.**

***Index Terms*—Geomagnetically induced currents (GICs), large-scale power systems, transformer protection, transmission line switching.**

I. Introduction

SOLAR coronal holes and coronal mass ejections can disturb the Earth's geomagnetic field. These geomagnetic disturbances (GMD) in turn induce electric fields which drive low-frequency currents in the transmission lines. These geomagnetically induced currents (GICs) can cause increased harmonic currents and reactive power losses by causing transformers half-cycle saturation. This may cause voltage instability by a combination of two means. First, the increased transformer reactive power losses may lead directly to voltage instability. Second, the harmonic currents might cause relay misoperation and unintended disconnection of the reactive power providers such as static VAR compensators [1]–[4].

Several techniques have been investigated in the literature to mitigate the GMDs [5], [6]. One technique is to install GIC blocking devices with the capacitive circuits at the transformer neutral. To reduce the cost, optimization techniques are developed to find their optimal placement [7], [8]. Series capacitors [8], polarizing cells [9], and neutral linear resistance [9], [10] are other types of GIC blocking devices investigated in the literature. The existing controls such as generator redispatch, load shedding, and line switching can mitigate GMDs with no additional employment cost. An optimal line switching is developed in [11] through formulating an AC-OPF that allows for topology reconfiguration and accounts for GIC-induced transformer thermal heating. The effectiveness of this algorithm is demonstrated on a small network and developing a scalable algorithm for large systems is left as future work. Reference [12] proposes a line switching strategy based on linear sensitivity analysis for large-scale power systems. This algorithm focuses on improving the overall security of the system through minimizing the total GIC-saturated loss and the safety of the individual transformers is not captured in the formulation. This paper builds on the existing literature on the line switching for GMD mitigation with more focus on the transformers safety and also scalability to large systems. The goal is to develop a switching strategy that satisfies the transformer thermal constraints in large-scale power systems while providing sufficient ac-related security measures.

In this paper, a line switching strategy is developed to protect the transmission transformers from GMDs. The proposed solution minimizes the number of opened lines subject to satisfying the transformer thermal limits. Similar to the conventional line outage distribution factors (LODFs) [13], transformer LODFs (TLODFs) are defined as the sensitivity of the transformer GIC-saturated reactive power loss to line outages. Using the linear sensitivities, the problem of finding the optimal line switching is formulated as a mixed integer linear programming (MILP). For a large system, performing MILP on all the lines is computationally expensive. To reduce the complexity, heuristic strategies are designed to identify the critical lines that are more likely to be part of the optimal solution and the optimization is performed on the reduced system. Furthermore, the coupling between the AC power flow solution and the GIC flows is modeled and

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preliminary tools are developed to maintain sufficient ac-related security measures.

During severe storms, a feasible solution that satisfies all the loss constraints may not exist. To tackle this, a multi-action solution with alternating schedule is considered. Each action is designed to remove the stress from a subset of the overheated transformers and an alternating schedule is developed to execute the actions periodically. The transformers that remain overheated during one action can cool down while the other actions are being executed. This provides great flexibility during severe storms when a single action can not satisfy all the thermal limits. Moreover, the number of opened lines at a time are reduced which contributes to better ac-related security measures and the feasibility of the AC power flow solution. The effectiveness of the algorithm is demonstrated through numerical results using a 150-bus system and a 2000-bus case.

The paper is organized as follows: The GIC model is introduced in Section II and solving power flow including GICs is described in Section III. The proposed line selection algorithm is presented in Section IV. Section V demonstrates the proposed technique through numerical results. Section VI presents a conclusion and direction for future work.

II. GIC Modeling

To calculate the voltage potential induced on the transmission line, the E-field is integrated over the length of the line. Assuming uniform E-field, the DC voltage on the line between bus n and m is expressed in:

$$V_{nm} = E^N L_{nm}^N + E^E L_{nm}^E \tag{1}$$

where L_{nm}^N and L_{nm}^E denote the northward and eastward distances of the line (n, m); and E^N and E^E are the northward and eastward E-fields, respectively. The induced voltages are converted to the DC current injections through Norton Equivalent, and the total current injections are derived from Kirchhoffs current law (KCL) [3]. The vector of current injections is obtained by putting all the current injections together as given by $\mathbf{I}^{inj} = \mathbf{CE}$ where $\mathbf{E} = [E^N, E^E]^T$ is the vector of E-field and $\mathbf{C}$ depends on the length, orientation, and resistance of the lines [14].

The nodal network equations are written using KCL and the bus voltages are obtained from the current injections as expressed in:

$$\mathbf{V} = \mathbf{G}^{-1}\mathbf{I}^{inj} \tag{2}$$

where matrix $\mathbf{G}$ is similar to the bus admittance matrix except that it only captures the conductance values and is modified to include substation grounding resistances. The GIC flow between any two nodes is given by

$$I_{nm}^T = G_{nm}(V_n - V_m) \tag{3}$$

where g_{nm} is the (n, m)-th entry of the matrix $\mathbf{G}$.

A. GIC-saturated Reactive Power Loss

The GIC passing through the transformer increases its reactive power loss. GIC-saturated reactive power loss can be linearly related to the effective GICs as expressed in:

$$Q^{GIC} = KV^{pu}I^{GIC} \tag{4}$$

where Q^{GIC} is the GIC-saturated reactive power loss and V^{pu} is the per unit voltage magniture of the high side of the transformer. K is the transformer loss coefficient which mostly depends on the core type, e.g. single phase, three-legged three-phase and five-legged three phase. This parameter may be calculated by simplifying the transformer magnetizing curve into linear segments and determining the slope and knee point of each segment, e.g. two segments are considered for the single-phase transformers and three segments for the three-phase, shell transformers to describe the complicated AC and DC flux coupling in the core. Detailed calculation of the K-parameter based on the transformer core type is described in [2], [15], [16]. I^{GIC} is the effective GIC and is calculated based on the transformer type and winding configuration. For a grounded wye-delta transformer, I^{GIC} is simply the current in the grounded coil. For transformers with multiple grounded windings (-autotransformers), the effective current is a function of the current in both coils as expressed in [17]:

$$I^{GIC} = \frac{\alpha I_H + I_L}{\alpha} \tag{5}$$

where I_H and I_L are respectively the per phase DC current passing through the high side winding (-series winding) and low side winding (-common winding) and α is the transformer turn ratio.

B. Linear Sensitivity Analysis

The transformer LODF (TLODF) can be expressed as:

$$\Psi = [S_{ij}] = [\mathbf{q}_i^{(j)} - \mathbf{q}_i^0], \quad i \in \mathcal{T},\ j \in \mathcal{L} \tag{6}$$

where Ψ is the TLODF matrix, S_{ij} is the variation of GIC-saturated loss at transformer i caused by opening line j, $\mathbf{q}_i^{(j)}$ is the GIC-saturated loss at transformer i when line j is opened and $\mathbf{q}_i^0$ is the initial loss. $\mathcal{T}$ and $\mathcal{L}$ are the set of transformers and lines, respectively. An analytical technique may be developed to derive TLODFs as a function of the network parameters [18]. While traditional LODFs are derived from the line inductances and system topology, TLODFs depend on the line conductances, system topology and the substation grounding resistances and are derived using the same approach as LODFs. TLODs may be calculated offline as long as the status of the lines are known. Alternatively, they can be calculated online with negligible running time to capture the real-time line status. Note that the system operating condition such as load and generation does not affect the TLODFs and they solely depend on the system topology and the lines/transformers parameters.

C. Background on GMD Mitigation

Space weather satellites such as Solar Terrestrial Relations Observatory (STEREO), the Geostationary Operational Environmental Satellite (GOES), and the Polar Operational Environmental Satellite (POES) are employed to forecast solar storms. Earth-directed Coronal mass ejections can be forecasted

14−96 hours before they hit the Earth. More accurate predictions with K-index warning are provided 30 minutes in advance. CMEs last a few minutes to several hours, yet their effects can linger in the Earths magnetosphere and atmosphere for days to weeks. The 2003 Halloween Storm lasted from Nov 19 to Oct 7, whereas the 1989 (March 12−13) and 1921 (May 14−15) storms had shorter duration. Note that the intensity and polarity of the storm changes and power system protection is most needed during the severe hours.

Major utilities and ISOs have developed preliminary operating procedures to protect the network during severe storms. Different procedures are designed based on the severity of the storm. Storms with K-index smaller than K4 do not trigger any action. If K-index is larger than K4 and smaller than K7, a warning state is declared and the ISO notifies the transmission and generation owners. For storms with K-index of K7 and higher, alert state is declared and the following emergency procedures are executed with small variations among different ISOs [1], [19], [20]:

1) The MVA limit of the inter-area and internal transmission lines and transformers are reduced to a maximum of 90% of the normal rating where appropriate. 2) The planned outages are reviewed, their impact on the system is evaluated and the problematic outages are canceled if possible. 3) Generation redispatch is utilized to provide sufficient reactive power reserve, e.g., synchronous condensers are dispatched. 4) SVC and capacitor banks are added if available to avoid voltage drop. 5) Reclosing tripped capacitor banks and SVCs during severe storms are considered since they probably tripped due to relay malfunction rather than an actual damage. 6) The excitation of generators is adjusted to maintain the voltages within the acceptable range and protect the network from voltage swings. 7) Real-time contingency analysis is performed with a focus on voltage contingencies and the impact of tripping large capacitor banks and SVC is considered.

III. Power Flow Solution Including GICs

To solve power flow including the GICs, the GIC-saturated reactive power loss of each transformer is modeled as a constant current source. Adding these current sources changes the reactive power injections at the high voltage side of the transformers by:

$$Q_i \leftarrow Q_i - K V_i^{pu} I_i^{GIC} \tag{7}$$

where Q_i is the reactive power injection at bus i. The power balance equations are nonlinear and the most common technique for solving them is Newton-Raphson solution. This technique uses the first order Taylor series to linearize the power balance equations as expressed in:

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = -\mathbf{J}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{8}$$

where $\Delta P\,(-\Delta Q)$ is the vector containing all the real (-reactive) power imbalances and $\mathbf{J}$ is Jacobian matrix defined as:

$$\mathbf{J} = \begin{bmatrix} \dfrac{\partial \Delta P}{\partial \Delta\theta} & \dfrac{\partial \Delta P}{\partial \Delta|V|} \\ \dfrac{\partial \Delta Q}{\partial \Delta\theta} & \dfrac{\partial \Delta Q}{\partial \Delta|V|} \end{bmatrix} \tag{9}$$

The algorithm starts with an initial guess, uses (8) to update the states in each iteration and continues the process until the power mismatches are smaller than a threshold. Adding the GIC-related constant current sources modifies the entries of the Jacobian that correspond to the partial derivative of the reactive power to voltage magnitudes of the same bus:

$$\frac{\partial \Delta Q_i}{\partial \Delta|V_i|} \leftarrow \frac{\partial \Delta Q_i}{\partial \Delta|V_i|} - K I_i^{GIC} \tag{10}$$

The other entries of the Jacobian matrix stay unchanged.

IV. Multi-action Line Switching Algorithm

A maximum limit is defined for the GIC-saturated loss of each transformer based on its thermal rating and a transformer is considered overheated if its loss exceeds that limit. To find an effective line switching strategy, a MILP is designed which minimizes the number of opened lines subject to satisfying the transformer loss constraints:

$$\begin{aligned} \min \quad & \sum_{1 \le i \le L} \mathbf{y}_i \\ \text{s.t.} \quad & \Psi \mathbf{y} \le \mathbf{q}^{\max} - \mathbf{q}^0 \\ & \mathbf{y} = [\mathbf{y}_i] \in \{0, 1\} \end{aligned} \tag{11}$$

where $\mathbf{q}^0$ is the vector containing the GIC-saturated loss of all the transformers prior to any action, $\mathbf{q}^{\max}$ is the vector of the transformers maximum permissible loss and L is the number of lines. $\mathbf{y}$ is a binary vector of size L which indicates the state of the lines, e.g., $\mathbf{y}_i$ is 0 (-1) if line i is closed (-open).

For a large system, performing mixed integer programming on all the lines is computationally expensive. To reduce the complexity, the critical lines are identified and the optimization is performed on the reduced system. Moreover, the loss constraints for only the overheated transformers are included in the formulation. Let $\mathbf{s}^0$ and $\mathcal{C}$ be the sets of overheated transformers and critical lines, respectively. The reduced-order MILP is given by:

$$\begin{aligned} \min \quad & \sum_{1 \le i \le C} \mathbf{x}_i \\ \text{s.t.} \quad & \Psi(\mathbf{s}^0, \mathcal{C}) \mathbf{x} \le \mathbf{q}^{\max}(\mathbf{s}^0) - \mathbf{q}^0(\mathbf{s}^0) \\ & \mathbf{x} = [\mathbf{x}_i] \in \{0, 1\} \end{aligned} \tag{12}$$

$\mathbf{x}$ is the binary state vector of size C where C is the number of critical lines. We use the indexing notation $\mathbf{a}(\mathbf{b})$ for vector $\mathbf{a}$ and $\mathbf{b}$ to indicate the subvector of $\mathbf{a}$ that contains the entries corresponding to $\mathbf{b}$. For example, for $\mathbf{a} =$ [10, 11, 12] and $\mathbf{b} =$ [1, 3], we have $\mathbf{a}(\mathbf{b}) =$ [10,12]. Similarly, the notation $\mathbf{A}(\mathbf{b}, \mathbf{c})$ for matrix $\mathbf{A}$ and vectors $\mathbf{b}$ and $\mathbf{c}$ indicates the submatrix of

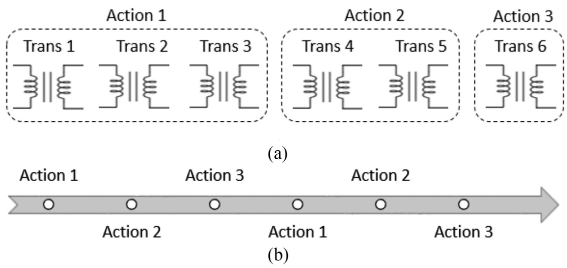

Fig. 1. Multi-action line switching framework. (a) Assigning the actions to the overheated transformers. (b) Timeline of the alternating schedule.

$\mathbf{A}$ that contains the rows corresponding to $\mathbf{b}$ and the columns corresponding to $\mathbf{c}$.

The GIC-saturated losses may be significantly large during severe storms and no switching action may be able to reduce them to below the limit. To tackle this, we consider an alternating solution; a switching action is designed to satisfy half of the constraints and another action to satisfy the other half. Employing the first action for half of the time and the second solution for the remaining time can reduce the stress from all transformers. The transformers that are overheated under the first solution, can cool down while the second solution is executed and vice versa. This idea can be extended to multiple solutions instead of just two. Each solution is designed to relax constraints on certain transformers and an alternating schedule is developed to execute the actions periodically as illustrated in Fig. 1.

A. Overview of the Algorithm

An overview of the proposed line switching algorithm is presented here (Algorithm 1) while the details are discussed in the following subsections:

The GIC power flow is solved, the transformer GIC-saturated losses are calculated and the set of overheated transformers, $\mathbf{s}^0$, is obtained. Critical line identification is performed to get the critical lines as detailed in Algorithm 2. Recursive MILP is performed to get the switching actions as detailed in Algorithm 3. This algorithm takes the overheated transformers as input and generates a set of actions that can remove their stress.

Recursive MILP divides the original problem into subproblems and calculates the action for each subproblem. There might be corner cases for this process and some of the overheated transformers may not be covered by any of the actions. Moreover, some of the transformers there were not initially overheated might become overheated as a result of the switching actions used for relieving other transformers. To avoid this, we find the transformers that stay overheated during all the actions in the solution set and perform an additional recursive MILP on those transformers. A transformer stays overheated if none of the actions can reduce its loss to below the limit. We refer to such transformers as posterior overheated transformers. The posterior overheated transformers are identified and recursive MILP is performed on them. The actions obtained from the second Recursive MILP are added to the results from the first one.

The final step of the algorithm is to remove the redundant actions as detailed in Algorithm 4. This step reduces the implementation complexity. The actions obtained from the first recursive MILP (seventh step of Algorithm 1) are referred to as prior actions, the ones added in the second recursive MILP (the ninth step) as the posterior actions and the ones remained after the filtering are the final actions. Note that the TLODfs are calculated only once at the beginning of the algorithm and remain unchanged through the recursions. The line status of the base case is used in each recursion and hence the TLODFs are not affected.

Algorithm 1: Multi-action Line Switching.

1: **procedure** LINE SWITCHING($\mathbf{q}^0$)
2: Solve GIC flow and calculate the initial loss, $\mathbf{q}^0$.
3: Calculate the TLODF matrix, Ψ.
4: Identify the overheated transformers, $\mathbf{s}^0$.
5: Find Critical lines through $\mathcal{C} =$ CRITICALLINE$(\Psi, \mathbf{s}^0)$.
6: Initialize the line switching matrix, $\mathbf{X}$ and the loss matrix,$\mathbf{Q}$ to empty matrices.
7: Perform Recursive MILP on the overheated transformers $[\mathbf{X}, \mathbf{Q}] = RecursiveMILP(\Psi, \mathbf{s}^0, \mathbf{q}^0, \mathcal{C}, \mathbf{X}, \mathbf{Q})$
8: Identify the posterior overheated transformers, $\mathbf{s}^p$.
9: Perform Recursive MILP on the posterior overheated transformers $[\mathbf{X}, \mathbf{Q}] = RecursiveMILP(\Psi, \mathbf{s}^p, \mathbf{q}^0, \mathcal{C}, \mathbf{X}, \mathbf{Q})$
10: Eliminate redundant switching actions through $[\mathbf{X}] = Filter(\mathbf{X}, \mathbf{Q})$
11: **return** $\mathbf{X}$
12: **end procedure**

Algorithm 2: Critical Line Identification.

1: **procedure** CRITICALLINE (Ψ^0)
2: Exclude the lines whose $\Delta Q_i^{\max}$ exceeds the threshold.
3: Calculate the overheated TLODF matrix, Ψ^o to include only rows corresponding to the overheated transformers.
4: Calculate $\mathbf{q}^T$ from the Ψ^O.
5: Sort the lines based on $\mathbf{q}^T$ in descending order.
6: Select the top C lines in the sorted list as the critical lines, $\mathcal{C}$.
7: **return** $\mathcal{C}$.
8: **end procedure**

B. Critical Line Identification

The critical line identification algorithm takes the overheated transformers as input and identifies the lines that are more likely to be part of the optimal solutions (Algorithm 2). Details of the algorithm are as follows:

Construct the overheated TLODF matrix, Ψ^O by including only the rows corresponding to the overheated transformers. The total loss reduction within the overheated transformers from opening a line is obtained by taking the sum of the overheated TLODF matrix along its corresponding column. Let

$\mathbf{q}^T = Sum(\Psi^O, 2)$ be the sum of the overheated TLODF matrix along the columns. The critical lines are obtained by sorting $\mathbf{q}^T$ in descending order and selecting the first C lines in the sorted list (negative values with largest magnitude). C is the desired number of critical lines, which is defined by the user to control the complexity.

This approach focuses on the overheated transformers and selects the lines which reduce their losses the most. Although it is important to prioritize the overheated transformers, it is desired to have some basic considerations for the other transformers as well. Motivated by this, the lines that increase the losses of any of the transformers by more than a threshold value (when opened) are excluded from the critical lines. Let $\Delta Q_i^{\max}$ be the maximum of the ith column of the TLODF matrix, which provides the largest loss increase among all transformers when line i is opened. The lines whose $\Delta Q_i^{\max}$ exceeds some user-defined threshold, $\Delta\bar{Q}$, are excluded from the critical lines. $\Delta\bar{Q}$ is termed as the maximum loss sensitivity limit. The value of $\Delta\bar{Q}$ for each transformer may be set to its maximum permissible loss or more accurately, the gap between the permissible loss and its loss prior to any action.

C. Recursive MILP Algorithm

During severe storms, a feasible solution that satisfies all the loss constraints may not exist. To handle this, a recursive MILP algorithm is designed which divides the original problem into smaller subproblems with fewer constraints and solves them recursively. Each step of the recursion takes the list of actions obtained from the previous steps as input, adds any new action generated in that step to the list and passes it out to the next step. Let $\mathbf{X}$ be the matrix containing the list of the previous actions where each column is one action. $\mathbf{Q}$ is the matrix of the resulting transformer losses for all the actions with columns corresponding to each action. The recursive MILP algorithm is summarized in Algorithm 3 and the details are as follows:

MILP is performed on the overheated transformers. If it has a solution, we solve ACPF including GICs using the line configuration from that solution. If the power flow solution is feasible, we add the solution and its corresponding losses to the input action and loss sets ($\mathbf{X}$ and $\mathbf{Q}$), respectively. If the MILP or the ACPF does not have a solution, we divide the set of overheated transformers into two subsets, $\mathbf{s}^L$ and $\mathbf{s}^R$. Recursive MILP is performed on the two subsets separately. The output actions obtained from the first Recursive MILP are used as inputs of the second one as shown in steps 11 and 12 of Algorithm 3. The outputs of the second Recursive MILP are the final outputs of the main function.

The procedure for dividing the transformers into two subsets is as follow: The reduced TLODF matrix, $\Psi(\mathbf{s}, \mathcal{C})$ is constructed by selecting the rows corresponding to overheated transformers and the columns corresponding to the critical lines. The pairwise correlations between the rows of the reduced TLODF matrix are calculated and the corresponding correlation matrix is constructed. Next, agglomerative hierarchical clustering is performed using the correlation matrix as the distance metric and the overheated transformers are divided into two clusters.

Algorithm 3: Recursive MILP.

1: **procedure** RECURSIVE MILP($\Psi, \mathbf{s}, \mathbf{q}^0, \mathcal{C}, \mathbf{X}, \mathbf{Q}$)
2: $[\mathbf{x}, \mathbf{q}] = MILP(\Psi, \mathbf{s}, \mathbf{q}^0, \mathcal{C})$
3: **if** MILP has a solution **then**
4: Solve ACPF using action $\mathbf{x}$.
5: **end if**
6: **if** MILP and ACPF both have solutions **then**
7: $\mathbf{X} \leftarrow [\mathbf{X}, \mathbf{x}]$
8: $\mathbf{Q} \leftarrow [\mathbf{Q}, \mathbf{q}]$
9: **else if** length($\mathbf{s}$) >1 **then**
10: Divide $\mathbf{s}$ into two subsets of the same size S^L, and S^R
11: $[\mathbf{X}^L, \mathbf{Q}^L] = RecursiveMILP$ $(\Psi, \mathbf{s}^L, \mathbf{q}^0, \mathcal{C}, \mathbf{X}, \mathbf{Q})$
12: $[\mathbf{X}, \mathbf{Q}] = RecursiveMILP$ $(\Psi, \mathbf{s}^R, \mathbf{q}^0, \mathcal{C}, \mathbf{X}^L, \mathbf{Q}^L)$
13: **end if**
14: **return** $\mathbf{X}, \mathbf{Q}$
15: **end procedure**

Algorithm 4: Redundant Actions Filter.

procedure FILTER($\mathbf{X}, \mathbf{Q}$)
Eliminate the actions that increase the loss of any transformer to more than the instantaneous limit, Q^{inst}.
for $1 \leq i \leq$ Number of Actions **do**
Construct $\mathbf{Q}^{(-i)}$ by excluding the ith column from $\mathbf{Q}$.
Calculate $\mathbf{q}^{(\min,-i)}$ by taking the minimum of $\mathbf{Q}^{(-i)}$ over the rows.
Calculate the violation index for $\mathbf{q}^{\min,(-i)}$.
end for
Sort the actions based on the violation index of their $\mathbf{q}^{\min,(-i)}$ in ascending order.
Select the top M actions in the sorted list as final actions, $\mathbf{X}^{Final}$.
return $\mathbf{X}^{Final}$
end procedure

The transformers within the same cluster are expected to have similar TLODFs, i.e., opening the critical lines have similar impacts on them (increase or decrease their reactive loss); hence, the MILP that groups them together is more likely to have a solution.

D. Filtering Redundant Actions

The switching actions are calculated independently at different steps of the algorithm and may have overlaps. Multiple solutions may relax the same set of transformers constraints and eliminating the redundant actions can still satisfy all the constraints. The algorithm to filter the redundant actions is as follows (Algorithm 4):

One switching action is excluded from the solution set and the amount of constraint violation obtained from the remaining actions is evaluated. Let $\mathbf{X}^{(-i)}$ be the set of actions excluding action i, $\mathbf{Q}^{(-i)}$ be its corresponding loss and $\mathbf{q}^{\min,(-i)} = \mathrm{Min}(\mathbf{Q}^{(-i)}, 1)$ be its minimum along the rows. A violation index is defined to evaluate the overall amount of loss violations among all transformers:

$$ViolationIndex(\mathbf{q}) = \sum_{i \in \mathcal{T}} \max\{0, \mathbf{q}_i - \mathbf{q}_i^{\max}\} \tag{13}$$

where $ViolationIndex(\mathbf{q})$ is the violation index of the system when the vector of transformer losses is $\mathbf{q}$. The violation index of $\mathbf{q}^{\min,(-i)}$ is used as a criterion to evaluate the contribution of action i to the overall performance. An action is more critical when the violation index of its $\mathbf{q}^{\min,(-i)}$ is higher, i.e., the system experiences more overheating if that action is excluded. The actions are sorted based on the violation index of their $\mathbf{q}^{\min,(-i)}$ in ascending order and the top M actions in the sorted list are selected as the final actions. M is the desired number of actions, which is defined by the user to control the implementation complexity.

It is possible that an action increases the loss in some of the transformers dramatically since the MILP formulation considers only the overheated transformers and the loss at other transformers remains unchecked. We define the instantaneous loss limit, Q^{inst} as the maximum loss that a transformer can withstand at any instant of time without any damage. Note that the loss limit, $Q^{\max}$, which was defined previously relates to the continuous loss and has a smaller value than the instantaneous limit. The actions that increase the loss of any transformer to more than the instantaneous loss limit are excluded.

E. Improving AC Security Measures

The transformers experience increased reactive power loss and overheating during GMDs and protecting them through line switching is desired. However, opening a line changes the AC flows in the system and may compromise the system security. Hence, a meaningful line switching algorithm should consider some aspects of the AC analysis along with the already existing GIC-related measures.

First, the proposed critical line identification uses only TLODFs as a criterion for selecting the best lines. The AC line flow may be considered as an additional criterion to improve the AC security measures:

$$F_i = \frac{Q_i^T}{\bar{P}_i} \tag{14}$$

where $\bar{P}_i$ is the flow on line i. F is calculated for all the lines and the line with the highest absolute value of F is selected in each iteration. This criterion favors the line that reduces the GIC-saturated loss more and also has lower AC flow on it.

Second, the objective function of the MILP may be modified such that opening the lines with high flows is penalized:

$$\begin{aligned} \min \quad & \sum_i \mathbf{x}_i + \lambda \sum_i |\bar{P}_i| \mathbf{x}_i = \sum_i (1 + \lambda |\bar{P}_i|) \mathbf{x}_i \\ \text{s.t.} \quad & \Psi(\mathbf{s}^0, \mathcal{C}) \mathbf{x} \le \mathbf{q}^{\max}(\mathbf{s}^0) - \mathbf{q}^0(\mathbf{s}^0) \\ & \mathbf{x} = [\mathbf{x}_i] \in \{0, 1\} \end{aligned} \tag{15}$$

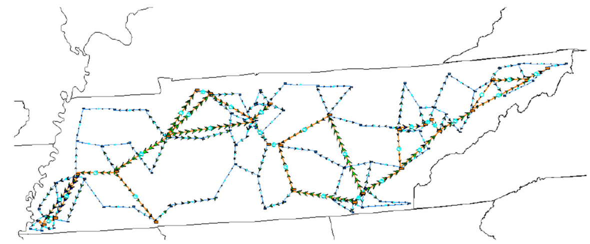

Fig. 2. One-line diagram of the150-bus synthetic system. The green lines are 500 kV and the blue lines are 230 kV.

where $\bar{P}_i$ is the active power on line i. λ is the weighting parameter which regulates the importance of the number of opened lines versus the total ac flows on the opened lines in the objective function. The motivation for adding the second term to the objective function is that when a line with high flow is opened, its flow will be redirected to other lines and might cause overloading on other lines.

A voltage violation index may be defined to speculatively evaluate the resultant security of the system after executing the line switching scheme. The total amount of voltage violation is calculated by:

$$\begin{aligned} & V_i^{\min} \le V_i \le V_i^{\max} \\ & SV = \sum_i \max\{0, V_i - V_i^{\max}, V_i^{\min} - V_i\} \end{aligned} \tag{16}$$

where V_i is the per unit voltage magnitude at bus i. $V_i^{\min} = 0.95$ pu and $V_i^{\max} = 1.05$ pu are typically considered in reliability studies and hence are used in this paper. Similarly, the security index for the line flows is given by

$$SI = \sum_i \frac{\max\{0, \bar{P}_i - P_i^{\max}\}}{P_i^{\max}} \tag{17}$$

where $P_i^{\max}$ is the flow limit of line i.

V. Numerical Results

In this section, the algorithm is applied to a 150-bus and a 2000-bus system and its performance is evaluated through numerical results.

A. 150-bus System

The first system to study is a 500/230 kV 150-bus synthetic system in [21], [22] with the one-line diagram illustrated in Fig. 2. An electric field with the magnitude of 6 V/km and the orientation of 26 °N is enforced to the system. This orientation results in the largest GICs for the system and hence is considered for the analysis. The GIC flow is solved and the resulting GIC-saturated loss is calculated. Without loss of generality, it is assumed that the maximum permissible loss, $Q^{\max}$, is 100 Mvar, the instantaneous loss limit, Q^{inst} is 200 Mvar and the maximum loss sensitivity, $\Delta\bar{Q}$ is 50 Mvar for all transformers. Other values may be considered for loss limits if real data on the transformers thermal ratings become available. The weighing parameter λ is assumed to be 0.1 throughout the paper. With these assumptions, the losses at 11 transformers exceeds

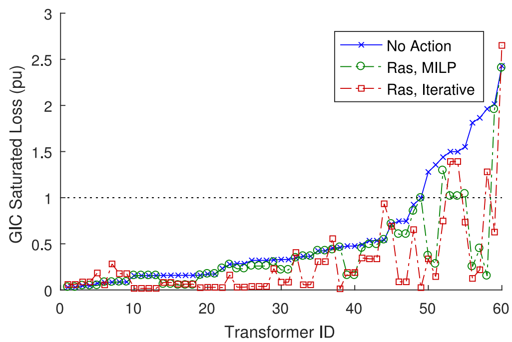

Fig. 3. Impact of the generated switching actions on the GIC-saturated loss of the individual transformers for the 150-bus system. The magnitude of the enforced E-field is 8 V/km.

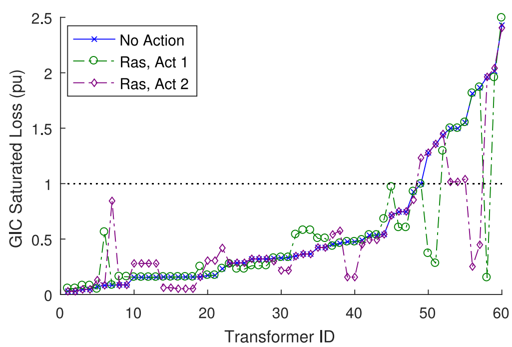

Fig. 4. Comparing the performance of the iterative algorithm with the MILP one in reducing the transformers GIC-saturated loss for the 150-bus system.

the limit and the resulting transformer violation index is 7.71 as calculated by (13). setting the number of actions to two, the algorithm generates two switching actions which reduce the transformer violation index to 2.72. The number of opened line is four for both actions with one reducing the transformer violation index to 5.97 and the other to 4.79. Fig. 3 illustrates the impact of the final actions on the GIC-saturated loss of the individual transformers. The transformer IDs denote the ranks of the transformers when sorted based on their initial loss, $\mathbf{q}^0$. It is observed that each action target only part of the overheated transformers and the algorithm is effective only when a combination of both actions is utilized.

The performance of the proposed strategy in reducing the transformers GIC-saturated loss is compared with the iterative technique in [12] as shown in Fig. 4. A summary of this algorithm is as follow: The best line to open is calculated based on TLODFs, the line is opened and the TLODFs for the new system is calculated. The next best line is calculated for the new system and this process is repeated until the total loss is reduced to some desired value. For the MILP technique, the GIC-saturated loss of each transform is the minimum of the losses from the two actions to capture the alternating schedule between the actions and account for the cooling down process. To have a peer comparison, the number of opened lines in the iterative algorithm is set in a way that the resulting solution provides the same transformer violation index as the one from MILP. Simulation results indicate that the iterative algorithm needs to open 20 lines to achieve a transformer violation index

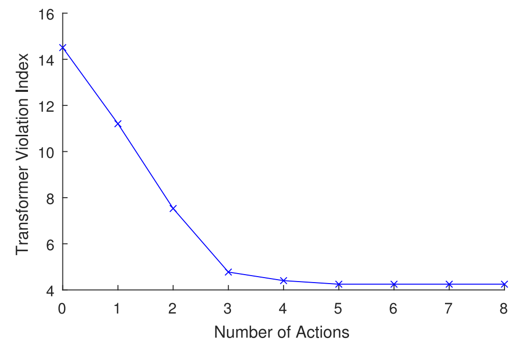

Fig. 5. Impact of the number of actions on the resulting violation index for the 150-bus system. The enforced E-field has a magnitude of 8 V/km.

TABLE I
PERFORMANCE OF THE ALGORITHM FOR THE 150-BUS SYSTEM UNDER DIFFERENT E-FIELD MAGNITUDES

Strategy	Violation Index			# of opened Lines	Total Loss (pu)
	Transformer	Line Flow	Voltage		
E-field=4 V/(km)					
No Action	1.76	0.36	-	-	22.8
Iterative	0.76	NaN	0.09	25	10.6
Action 1	0.27	0.62	0.00	5	19.8
Action 2	1.49	0.47	-	5	23.34
Mixture	-			5	
E-field=6 V/(km)					
No Action	7.71	1.03	0.00	-	34.23
Iterative	2.71	4.36	0.08	20	18.21
Action 1	5.97	1.05	0.00	4	31.7
Action 2	4.79	2.34	0.00	4	30.4
Mixture	2.72			4	
E-field=8 V/(km)					
No Action	14.51	2.04	0.01	-	45.6
Iterative	7.04	3.05	0.02	15	30.8
Action 1	10.9	2.38	0.02	4	36.9
Action 2	11.4	2.82	0.07	3	42.8
Mixture	7.82			3,4	

Running Time is 0.26 s,1.32 s and 1.7 s when E-field is 4 V/km, 6 V/km and 8 V/km, respectively.

of 2.71. This is significantly higher than the number of opened lines in the MILP technique (four lines). As illustrated in the figure, the iterative algorithm reduces the losses in many transformers including the ones that are not overheated whereas the MILP strategy targets only the overheated transformers with little impact on the others. Note that the objective of the iterative algorithm is to reduce the total loss in the network without any focus on the overheated transformers. The total loss prior to any action is 34.23 (pu), the iterative algorithm with 20 opened lines reduces this value to 18.21. The total loss from the two actions of MLIP strategy are 31.7 and 30.42, not much smaller than the value prior to any action.

Increasing the number of actions, M, reduces the violation index as shown in Fig. 5. However, this increases the employment complexity and reduces the time percentage allocated to each action ($\frac{1}{M}$). If the time duration of an action is too short, the overheated transformers covered by that action might not have enough time to cool down. More detailed thermal modeling of transformers will be considered in future studies to calculate the minimum time required for the transformers to cool down.

Next, the performance of the algorithm under different levels of storm severity is evaluated. Table I presents the performance

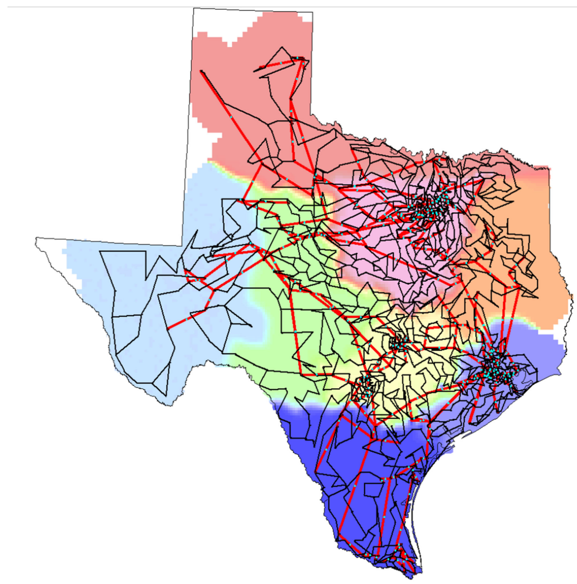

Fig. 6. One-line diagram of the 2000-bus synthetic system. (a) Eight geographic areas are color-coded. (b) Red lines are 345 kV and black lines are 115 kV.

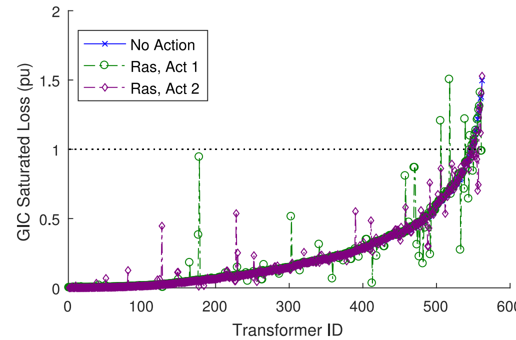

Fig. 7. Impact of the generated switching actions on the GIC-saturated loss of the individual transformers for the 2000-bus system. The magnitude of the enforced E-field is 8 V/km.

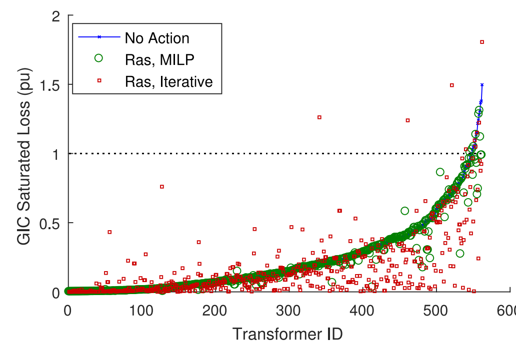

Fig. 8. Comparing the performance of the iterative algorithm with the MILP one in reducing the transformers GIC-saturated loss for the 2000-bus system.

when the magnitude of the enforced E-field varies from 4 V/km to 8 V/km. The algorithm generates two actions when E-field is 4 V/km and reduces the violation index from 1.76 to 0. For reference, the line flow, voltage and transformer violations, the number of opened lines by each action, and the total loss among all transformers are also presented in the table. Moreover, for each MILP strategy, the results of the iterative algorithm with the same transformer violation index is presented. It is observed that for all cases, the iterative algorithm requires opening more line and provides a solution that has weaker stability measures (voltage and line flow violation indices). Again, this is because the iterative algorithm focuses on reducing the total GIC-saturated loss without any special treatment for the overheated transformers (notice the smaller values of the total loss for this algorithm in the table). On the other hand, the MILP approach reduces the loss in the overheated transformers while possibly increasing it at other transformers. Therefore, the total loss is not necessarily reduced. The objective of the algorithm is to remove the stress from the overheated transformers as opposed to minimizing the total loss. The running time of the algorithm for the 150-bus system is 0.26 s, 1.3 s and 1.7 s when E-field is 4 V/km, 6 V/km and 8 V/km respectively. The computations are performed on a Dell XPS 8900 system with Intel core i7, 16GB RAM. Note that the running time increases with the E-field magnitude. This is because the loss violations are more significant at higher E-field magnitudes and more recursions are required to reach a small enough subproblem that has a solution.

B. 2000-bus System

The second system to study is a 2000-bus synthetic system with the one-line diagram shown in Fig. 6 [22], [23]. An electric field with 8 V/km magnitude and 91 °N orientation (the direction with highest GICs) is enforced to the system. Prior to any action, 14 transformers are overheated and the violation index is 2.86. Since the system is large with 3024 lines, critical line identification is performed to reduce the search space to 500 lines ($C = 500$) and the maximum number of opened lines is set to 10. The algorithm generates two actions both with six opened lines which reduce the number of transformer loss violations to six and their violation index to 0.85.

The performance of the MILP technique in reducing GIC-saturated loss is compared with the iterative algorithm in Fig. 8. The solution from the iterative algorithm is desired to have the same transformer violation index as the one from MILPs to have a peer comparison. However, the lowest transformer violation index that can be achieved through the iterative algorithm is 2.32 and it requires opening 80 lines. This solution mostly reduces the loss of transformers that already have lower loss instead of relieving the overheated transformers as shown in the figure.

Fig 9 and 10 illustrates the voltage profile and the MW loading of the lines (flow divided by the MW limit) when the two actions from the MILP technique are employed. The bus IDs denote the bus ranking when sorted based on their magnitude prior to any action. Clearly, all the line flows and bus voltages are within their limit and the switching actions do not comprise the ac stability of the system.

Fig. 11 illustrates the impact of the number of actions on the violation index. Again, increasing the number of actions reduces the violation index, yet increases the implementation complexity and the time percentage allocated to each action.

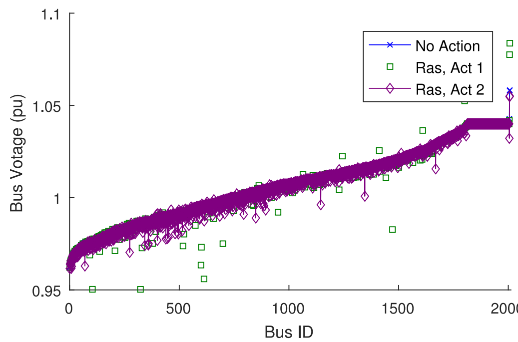

Fig. 9. Impact of the generated switching actions on the voltage profile of the individual transformers for the 2000-bus system. The magnitude of the enforced E-field is 8 V/km.

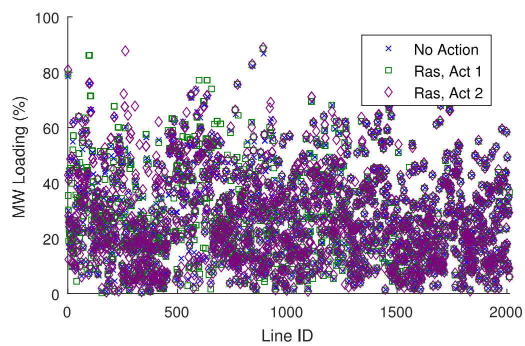

Fig. 10. Impact of the generated switching actions on line flows for the 2000-bus system. The magnitude of the enforced E-field is 8 V/km.

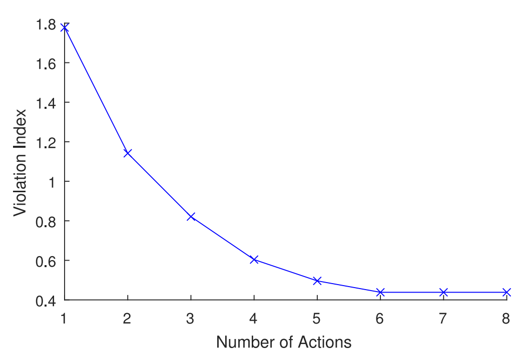

Fig. 11. Impact of the number of actions on the resulting violation index for the 2000-bus system. The enforced E-field has a magnitude of 8 V/km.

The operator should consider this tradeoff when selecting the maximum number of actions.

Table II presents the performance of the algorithm when the magnitude of the enforced E-field varies from 6 V/km to 12 V/km. Larger magnitudes are considered for this case compared to the 150-bus system since it is more resilient to GICs. When E-field is 6 V/km, the algorithm generates one action which successfully reduces the transformer violation index to zero by opening two lines. The iterative solution can not reduce the transformer violation index for the low E-field scenario as it is already relatively low and reducing the total loss without considering the overheated transformers results in a slight increase in the transformer violation index. The table presents three solutions for the 8 V/km E-field. The first solution has two actions and can reduce the violation index to 0.85 while maintaining the ac security measures. The second solution has three actions and reduces the violation index to 0.1. However, its second action has a voltage violation index of 1.15 which might compromise the system ac security. The third solution has only one action which requires opening 16 lines. This solution is obtained by increasing the limit on the number of opened lines from 10 to 20. This solution reduces the transformer violation index to zero, yet its voltage violation index is 1.18 and might cause voltage stability issues. Note that the algorithm can generate a variety of solutions by changing the user-defined inputs like the maximum number of lines and the number of actions. These solutions have different characteristics in terms of implementation complexity, transformer protection capability and ac security measures. The operator should consider such tradeoffs when selecting the best solution. Comparing the iterative algorithm with the MILP one, the lowest transformer violation index that can be achieved by the iterative algorithm is 2.32 which is still much higher than the ones obtained from the MILP solutions. The iterative solution requires opening 80 lines and the resulting voltage violation index is larger than 100 which puts the system in severe voltage instability. Similar results are observed when E-field is 12 V/km. The transformer violation index is 18.59 prior to any action. MILP strategy provides two actions which reduces the index to 12.3. The violation index obtained from using each action separately ranges from 16.9 to 17.3 and the algorithm is effective only when a combination of both actions is utilized. An equivalent solution from the iterative algorithm which provides similar transform violation index requires opening 80 lines and its voltage violation index is significantly high. Again, this is because the objective of the iterative algorithm is to minimize

TABLE II
PERFORMANCE OF THE ALGORITHM FOR THE 2000-BUS SYSTEM UNDER DIFFERENT E-FIELD MAGNITUDES

Strategy	Violation Index			# of opened Lines	Total Loss (pu)
	Trans-former	Voltage	Line Flow		
E-field=6 V/(km)					
No Action	0.18	0.02	-	-	97.2
Iterative	0.42	NaN	0.52	80	71.6
Action 1	0	0.01	0	2	96.9
E-field=8 V/(km)					
No Action	2.86	0.01	-	-	129.9
Iterative	2.32	NaN	0.77	80	91.2
Action 1	2.95	0.09	0	6	130.5
Action 2	1.94	0.01	0	6	130.8
Mixture	0.85	-	-	-	
No Action	2.86	0.01	0	-	129.9
Action 1	2.95	0.09	0	6	130.5
Action 2	2.51	1.15	0	5	129.0
Action 3	1.94	0.01	0	6	130.8
Mixture	0.05	-	-	5,6	-
No Action	2.86	0.01	0	0	129.9
Action 1	0	1.18	0	16	128.7
E-field=12 V/(km)					
No Action	18.59	0.01	0	-	194.4
Iterative	13.37	NaN	0.51	76	141.97
Action 1	17.3	0.00	0	5	191.5
Action 2	16.9	0.01	0	6	193.3
Mixture	12.3	-	-	-	

Running Time is 1.7 s,10.5 s and 92.4 s when E-field is 6 V/km, 8 V/km and 10 V/km, respectively.

the total loss in the system and does not necessarily relive the overheated transformers.

The running time of the algorithm for the 2000-bus system is 1.7 s,10.5 s and 92.4 when E-field is 6 V/km, 8 V/km and 12 V/km respectively. This is significantly low compared to the existing techniques that can take up to 2900 seconds for a 97-bus system [11]. Again, the running time increases with the E-field magnitude since at higher E-field magnitudes, more recursions are required to reach a small enough subproblem that has a solution.

VI. Conclusion

In this paper, a line switching algorithm is developed to protect the transmission transformers during GMDs. Using the linear sensitivity analysis, a mixed integer linear programming is formulated which minimizes the number of opened lines such that the transformer thermal limits are satisfied. The coupling between the AC power flow solution and the GIC flows is incorporated into the algorithm to provide sufficient ac-related measures. Moreover, Heuristic strategies based on linear sensitivities are designed to reduce the computational complexity for large-scale power systems. Finally, a multi-action framework is developed for severe storms when loss violations are significant and a single action can not eliminate all the violations. This further reduces the number of opened lines at a time and provides better voltage profile. The effectiveness of the algorithm is evaluated through numerical results using a medium-size 150-bus system, and a large 2000-bus case.

The paper suggests several directions for future research. First, the proposed algorithm schedules the actions within equal time intervals. However, the actions have different impacts on the transformers heating and it might be better to execute some actions for longer than the others. Future research tends to address this by performing detailed transformers thermal modeling and scheduling the actions accordingly. Second, the current formulation assumes a constant E-field and magnitude whereas the E-field evolves over time during actual storms. The algorithm can be further refined to capture time-extended E-fields and possibly use real measurements from actual storms as input.

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