Mitigation of Cascading Outages by Breaking Inter-Regional Linkages in the Interaction Graph

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***Abstract*—This paper proposes a scheme to isolate cascading outages in a local region by breaking inter-regional linkages of component failures. The scheme employs a data-driven inter-regional Interaction Graph on key linkages of component failures respectively from two different operating regions, which are indicators of the propagation of outages from a local region to the rest of the system. When the triggering of a key linkage is predicted to have a high risk, a remedial action that sheds an amount of load determined by sensitivity analysis is taken to mitigate the outages and stop their propagation. The proposed scheme is validated both on the IEEE 118-bus test system and an actual power grid model.**

***Index Terms*—Inter-regional interaction graph, cascading outages, mitigation scheme, hidden failure model, load shedding.**

I. Introduction

FOR modern power systems, cascading outages induced by complicated reasons have become the leading causes of large-scale blackouts [1]–[3]. As a large number of renewable energy sources are connected to the grid, the risk of complex cascading outages increases due to randomness and uncertainty factors. Once cascading outages are initiated and start to propagate, system operators need to quickly determine control targets and control measures to mitigate and stop outages. Therefore, online decision support to effectively mitigate propagating cascading outages still poses a big challenge to transmission system operators.

Cascading outages have been an important research topic for decades. Fruitful research findings have been achieved, such as cascading failure models, including hidden failure model [4], Manchester model [5], [6], CASCADE model [7], the collection of OPA models [8]–[14], dynamic and quasi-dynamic models [15]–[17], PRA model [18]. However, effective mitigation methods for cascading outages, especially online mitigation, are still preliminary.

Manuscript received 18 October 2021; revised 13 March 2022; accepted 7 May 2022. Date of publication 19 May 2022; date of current version 27 February 2023. This work was supported by the National Natural Science Foundation of China under Grant 51777196. Paper no. TPWRS-01629-2021. *(Corresponding author: Shiying Ma.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPWRS.2022.3175481.

Digital Object Identifier 10.1109/TPWRS.2022.3175481

Recently, study cascading outages and their mitigation methods based on graph methods has been developed rapidly. For instance, paper [21] proposed an interaction network to identify the critical components of a power system and key linkages of component failures under outage propagation using a dataset of cascading events. This model is improved in [22] by the Expectation-Maximization algorithm and then be further verified using actual utility outage data in [23]. Ref. [24] extended the single-layer interaction graph (IG) to a multi-layer IG, where each layer focuses on one aspect of outage propagation, e.g., the number of line outages, the amount of load loss, and the electrical distance of the outage propagation. In [25], the authors extended the IG model in [21] to a dynamic IG and proposed an online mitigation strategy against cascading outages using an optimal power flow model. A similar graph-based model called the "influence graph" was studied in [19] and [20], whose nodes represent cascading events and edges to measure influences between the cascading events.

The IG models on component failures and their linkages provide an effective way to understand the propagation mechanism of cascading outages and are promising for online applications. However, if an IG aims to cover all components of the entire system, it will require a massive amount of data from either historical or simulated events. Moreover, if all possible interactions are considered, such a graph can be very complicated. For instance, the number of linkages for a 118-bus system can be increased to thousands under some severe circumstances, such as heavily loaded scenarios. Too complex propagation relationships will confuse operators and restrict its online application since only a limited number of actions can be taken timely in operational timescales.

Practical mitigation of cascading outages often focuses on stopping propagation from a local operating region to the rest of the system. Thus, the linkages connecting operating regions will be more critical for a modern power grid having interconnected control regions. If paths of outage propagation are categorized into intra-regional paths, on which outages are still inside a region, and inter-regional paths, which propagate outages outside a region, inter-regional propagation paths are usually fewer than intra-regional paths. To void widely spread cascading outages, the operators can focus on mitigating inter-regional propagation paths so as to limit outages inside a local region, which can be controlled by remedial action schemes designed for the region.

Therefore, this paper proposed a scheme to isolate cascading outages in a local region by breaking inter-regional linkages of component failures. The scheme employs a data-driven Inter-regional Interaction Graph (for short, IRIG) focused on key linkages of component failures respectively from two different control regions, which are indicators of the propagation of outages from a local region to the rest of the system. When the triggering of a key linkage is predicted to have a high risk, a remedial action that sheds load by sensitivity analysis is taken to mitigate the risk to stop the outage from propagation.

The main contributions of this paper include:

1) This paper proposed a new idea that mitigates inter-regional cascading outages. The proposed mitigation scheme first assesses the inter-regional propagation risk based on the hidden failure hypothesis and IRIG. Then it focuses on breaking inter-regional linkages of component failures respectively from different operating regions. This scheme can isolate cascading outages in a local region with a small control cost.
2) Compared with the existing IG models, the complexity of the proposed IRIG can be significantly reduced, and it is more suitable for online applications.
3) The proposed mitigation control model considered the influence of online power flow, making it more accurate in online use than the IG model.

The rest of this paper is organized as follows. Section II introduces the proposed IRIG. Section III elaborates the risk assessment method of inter-regional cascading outages. Section IV elaborates the proposed mitigation scheme. Section V demonstrates the proposed models and mitigation scheme on the IEEE 118-bus system and an actual power grid model. Finally, this work is concluded in Section VI.

II. Inter-Regional Interaction Graph

An IRIG extracts important inter-regional information from an original IG and its nodes represent outage events on components, e.g., transmission lines or transformers, and its edges (or links) measure the interactions between different events.

Fig. 1 visualizes the topology of the IEEE 118-bus power system together with its IG and IRIG. The IG reflects key interactions between all outage events. Suppose that the grid is divided into two regions, region A and region B. Then IRIG keeps the inter-regional links of the original IG. For a large-scale power system, the IRIG largely simplifies the original IG.

A. Generating the Outage Database

The first step to build an interaction graph is to generate a database of cascading outage scenarios, which are called "cascades" in the rest of this paper. Any cascading outage simulation based on engineering principles can be used to produce the data needed to synthesize the interaction graph. Then group these data into different stages within each cascade based on the sequences or timing of outages. Assume that the size of the database is K, and m represents the stage. Assume M to be the maximum value of m. The grouped data can be illustrated as

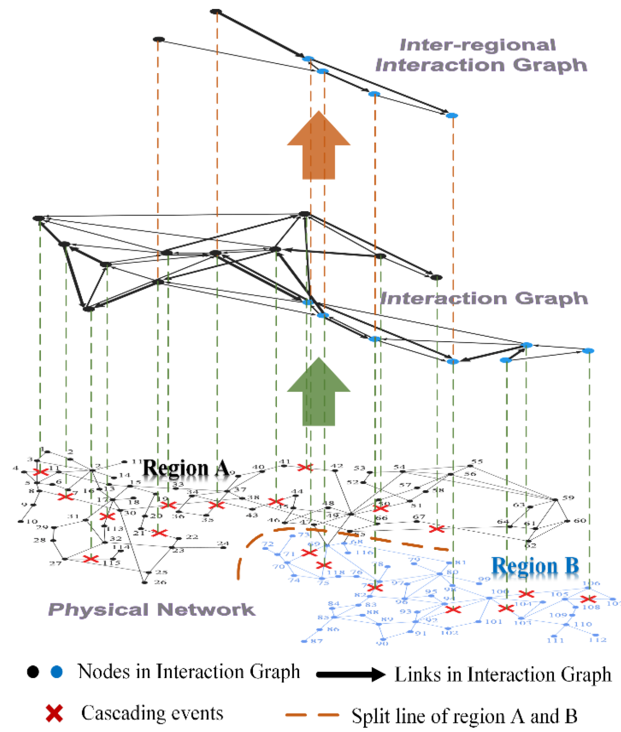

Fig. 1. The illustration of grid topology, interaction graph and inter-regional interaction graph.

follows:

$$\begin{array}{cccccc} & \text{Stage 0} & \text{Stage 1} & \cdots & \text{Stage m} & \cdots \\ \text{Cascade 1} & F_0^{(1)} & F_1^{(1)} & \cdots & F_m^{(1)} & \cdots \\ \text{Cascade 2} & F_0^{(2)} & F_1^{(2)} & \cdots & F_m^{(2)} & \cdots \\ \vdots & \vdots & \vdots & & \vdots & \\ \text{Cascade } K & F_0^{(K)} & F_1^{(K)} & \cdots & F_m^{(K)} & \cdots \end{array}$$

$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{M=\max\, m}$$

B. Building the Interaction Graph [21]

Firstly, construct a matrix $\boldsymbol{A} \in \mathbb{Z}^{n\times n}$ whose entry a_{ij} is the number of times that component i fails in one stage before the failure of component j among all cascades. n in matrix $\boldsymbol{A}$ is the number of failed components in the database (the same component is counted only once).

$\boldsymbol{A}$ cannot be used as the interaction matrix directly since it exaggerates the interactions between component failures; i.e., it asserts one component interacts with another one only because it fails in its last stage. Therefore, the causal relationships between failed components should be estimated and simplified. Specifically, for any two consecutive stages, m and $m+1$, of any cascade x, assume that the set of components in stage m is $\boldsymbol{C}_m$, and component j fails in stage $m+1$. In Ref. [21], the authors estimated and simplified the causal relationships through (1). Note that C_m is the set of failed components in stage m. The estimating process can be illustrated in Fig. 2.

$$a_{i_c j} = \max_{i \in C_m} a_{ij} \tag{1}$$

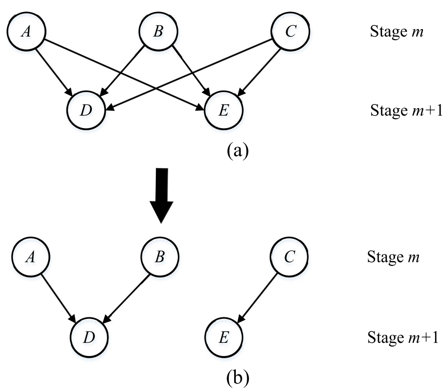

Fig. 2. Estimating process of two consecutive stages of a cascade.

Assume that two consecutive stages of a cascade and the values of the edges satisfy Eqs. (2) and (3).

$$a_{AD} = a_{BD} = \max_{i \in \{A,B,C\}} a_{iD} \tag{2}$$

$$a_{CE} = \max_{i \in \{A,B,C\}} a_{iE} \tag{3}$$

From Fig. 2(a) to (b), the edges $A \rightarrow E$, $B \rightarrow E$, and $C \rightarrow D$ are removed, i.e., the elements a_{AE}, a_{BE}, and a_{BE} are corrected to be 0. Therefore, the assumed causal relationships are that: the failures of A and B cause the failure of D; the failure of C causes the failure of E.

This process preserves the assumed causal relationships in stage m that are most likely to trigger events in stage m+1, and remove other less probable relationships. This assumption although requiring a further verification is often used in studies on IGs because of its simplicity if no further detailed information is available on causalities, e.g., reference [17], [24], [25].

$\boldsymbol{A}'$ is the simplified $\boldsymbol{A}$ matrix based on Eq. (1), and a'_{ij} is the element of matrix $\boldsymbol{A}'$. From a numerical point of view, a'_{ij} is the number of times that the failure of component i causes the failure of component j. When we normalize a'_{ij} by the total number of component i failures (N_i), we get the empirical probability that component i causes j failure, i.e., b_{ij}.

$$b_{ij} = \frac{a'_{ij}}{N_i} \tag{4}$$

The interaction matrix $\boldsymbol{B} \in \mathbb{Z}^{n \times n}$ estimates how components interact with each other. The nonzero elements of $\boldsymbol{B}$ are called links. By putting all links together, an IG denoted by $\boldsymbol{G}(\boldsymbol{C}, \boldsymbol{L})$ can be obtained. The detail of building IG can be found in [21].

Note that the IG model is improved in [22] and some following works, but the root is not changed (nodes represent outage events, and its edges measure the interactions). All these methods are acceptable to build the IG in this section.

C. Building the Inter-Regional Interaction Graph

Assume that the power grid has n control regions. Call the region where outages initiate as an "initial region" in the rest of this paper. Relatively, the other regions are grouped and named as "outer regions". Therefore, the purpose of the proposed mitigation control is to isolate the outages within the initial region.

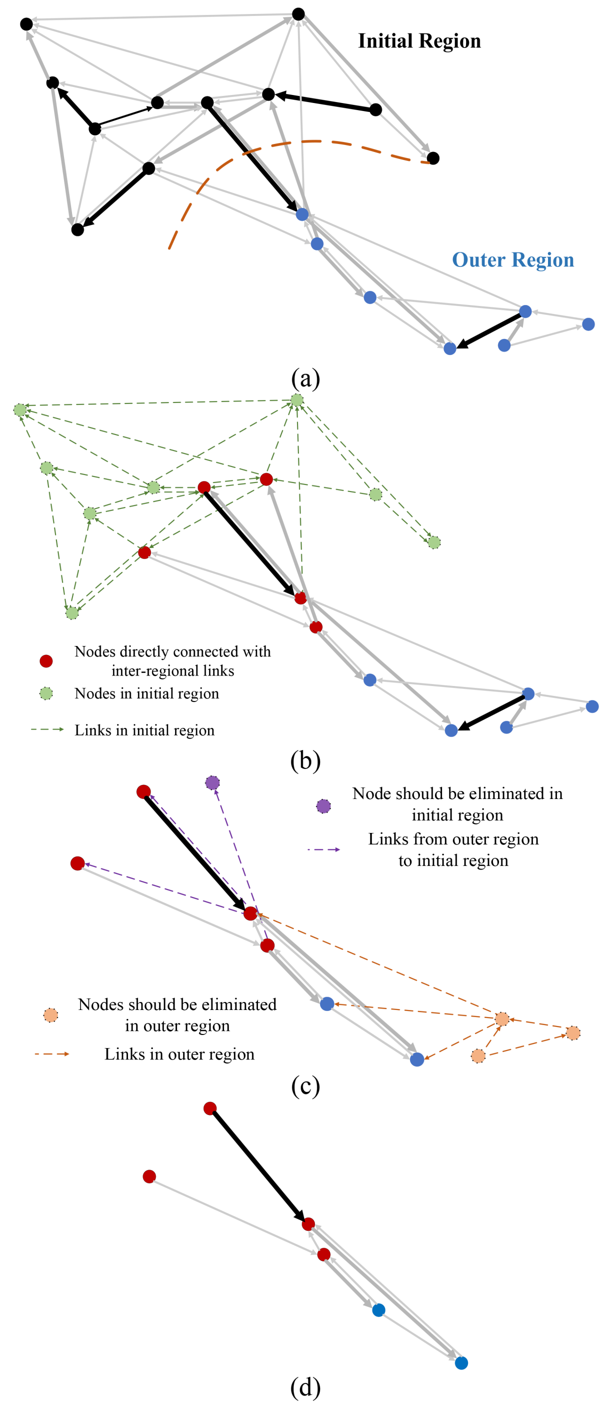

Fig. 3. Simplification process from IG to IRIG.

Fig. 3 illustrates the simplification process from IG to IRIG. Fig. 3(a) shows the original IG, the black nodes belong to the initial region, and the blue nodes belong to the outer region. The arrows are links, and the color and line thickness represent the weight of the links. Fig. 3(d) gives the IRIG. From Fig. 3(a) to (d), we need to remove three kinds of links and nodes:

Step 1 removes nodes and links inside the initial region as illustrated in Fig. 3(a) to (b) respectively by dashed green links and green circles. Therefore, the entry $\{b_{ij} \mid i \in R_{ini}$ and $j \in R_{ini}\}$ in matrix B is set to be 0, where R_{ini} and R_{out} are the initial region and outer region, respectively.

Step 2 removes links start from an outer region to the initial region as illustrated in Fig. 3(c) by purple dashed links. Here, we are concerned about the impact of the initial region on the outer region rather than the opposite direction. Therefore, the entry $\{b_{ij} \mid i \in R_{out}$ and $j \in R_{ini}\}$ is set to be 0.

Step 3 removes all links of the outer region that do not involve any node of the initial region as illustrated in Fig. 3(c) by orange dashed links and nodes. Therefore, these removed orange nodes do not significantly influence how outages from the initial region propagate to an outer region. On the other hand, the remain links in the outer region should be preserved since they are indispensable when calculating the propagation risk through the inter-regional linkages.

Let $\mathbf{C}_{\text{out}}$ denotes the set of all nodes in the outer region, and $\mathbf{C}_0$ denotes the nodes directly connected with inter-regional links (red circles in Fig. 3(c)). The strategy to determine which nodes or links to be removed is following:

- First, find all the nodes directly pointed to by C_0 in the remaining nodes ($C_{\text{out}} \backslash C_0$) and define them as set C_1. Note that ($C_{\text{out}} \backslash C_0$) mean Set C_{out} minus the elements of set C_0.
- Then, find all the nodes directly pointed to by C_1 in ($C_{\text{out}} \backslash C_0 \backslash C_1$) and define them as set C_2.
- Continue this process until there are no new nodes appear. The part of the graph that needs to be removed is the set of nodes ($C_{\text{out}} \backslash C_0 \backslash C_1 \cdots$) and all the related links.

After removing the above nodes and links, we can derive the IRIG, i.e., Fig. 3(d). Compared with the original IG, the IRIG is a significantly reduced graph focusing on mitigation of inter-regional outage propagation.

III. Risk Assessment on Inter-Regional Outage Propagation

To assess the risk of the propagation of inter-regional cascading outages, an index K_l is defined as the expected value of the number of outages propagated through the inter-regional link l: $i \rightarrow j$. The inter-regional links are defined as follows:

$$\boldsymbol{L}_{\text{int}} = \{l : i \rightarrow j \,|\, i \in R_{ini} \,\text{and}\, j \in R_{out}\} \tag{5}$$

where R_{ini} and R_{out} are the initial region and outer region, respectively.

K_l can be calculated through a unique directed acyclic subgraph extracted from the IRIG $\boldsymbol{G}_{IRIG}$.

Fig. 4 illustrates the process of obtaining the directed acyclic subgraph $\boldsymbol{G'}_{ij}$, which is corresponding to link l: $i \rightarrow j$. Fig. 4(a) is the original subgraph extracted from $\boldsymbol{G}_{IRIG}$. Note that vertex (component) i is not in Fig. 4 since K_l is defined on the condition of i failed.

From Fig. 4(a) to (b), the vertices for which there is no path from vertex j to them [H, I, and J, dashed circles in Fig. 4(a)] and the corresponding edges [$H \rightarrow j$, $I \rightarrow D$ and $J \rightarrow E$, dotted arrows] are removed since they cannot be influenced by j. Then

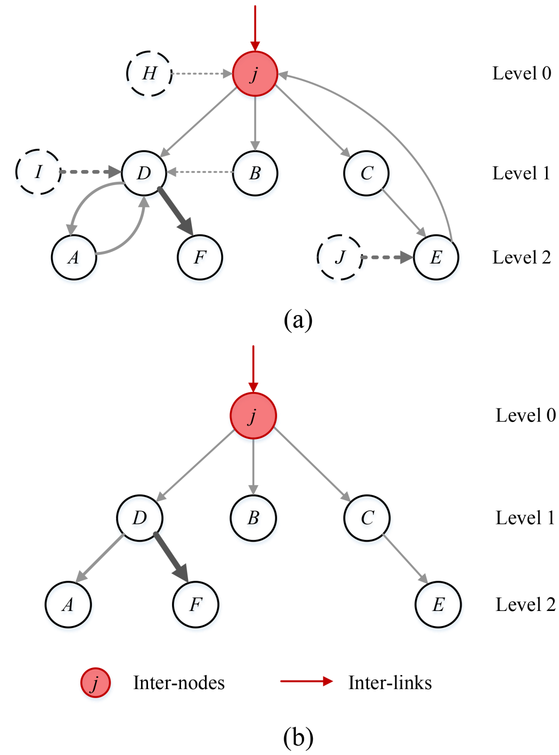

Fig. 4. Diagram for obtaining the directed acyclic subgraph starting with j.

the edges from vertices at a higher level to those at a lower level [$A \rightarrow D$ and $E \rightarrow j$, dotted arrows] and the edges between vertices at the same level [$B \rightarrow D$, dotted arrow] are also removed. Note that there are dependencies between the vertices at the same level. They are removed in order to convert the original directed cyclic graph into a tree so that the calculation can be simplified.

Finally, a directed acyclic subgraph $\boldsymbol{G}'(j, i \rightarrow j, 0)$ [Fig. 4(b)] is obtained for which there is no loop, and for each vertex, there is exactly one vertex pointing to it.

The index K_l for each link is defined as

$$K_l = \sum_{k \in \mathbf{C'}_{ij}} E_s b_{sk} \tag{6}$$

where $\boldsymbol{C'}_{ij}$ is the set of vertices in $\boldsymbol{G'}_{ij}$; E_s is the number of failures of the source vertex pointing to vertex k, e.g., for vertex D, $E_s = N_j b_{jD}$; b_{Sk} is the S^{th} row and k^{th} column element of interaction matrix $\boldsymbol{B}_{IRIG}$. Note that the source vertex pointing to j is i.

Based on index K_l, the propagation risk of inter-regional cascading outages can be further assessed. Fig. 5 illustrates the process of estimating the propagation risk. There are three successive cascading stages, i.e., Stage x, Stage x + 1, and Stage x + 2, and Stage x is the current operating state. Assuming that components B and D are overloaded, the links related to them will be riskier than other links. Therefore, the propagation risk is not only related to K_l but also related to the load ratio of the component.

By modelling the probability that a line tripped incorrectly as a piecewise function of line flow [26], as shown in Fig. 6. The

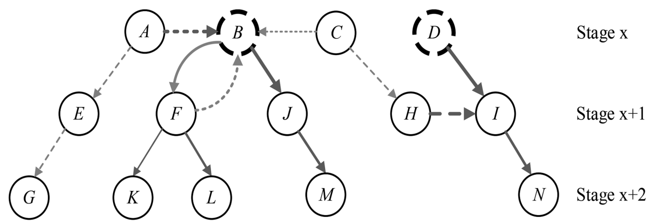

Fig. 5. The process of estimating the propagation risk.

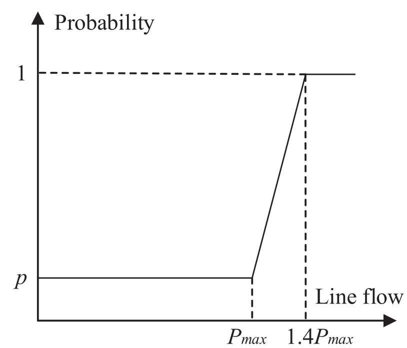

Fig. 6. Probability of a line tripping incorrectly. Here, p refers to the mis-operation probability and $P_{\max}$ is the line limit.

propagation risk of inter-regional cascading outages throws link l can be calculated by:

$$P_{\text{int},l} = K_l \times f(P_i) \tag{7}$$

$$f(P_i) = \begin{cases} p_i, & P_i \leq P_{i\max} \\ \frac{1-p}{0.4P_{i\max}} \times P_i + 3.5p - 2.5, & P_{i\max} < P_i < 1.4P_{i\max} \\ 1, & P_i \geq 1.4P_{i\max} \end{cases} \tag{8}$$

where P_i is the power flow on component i; $f(P_i)$ is the probability of i outage incorrectly, i.e., the piecewise function in Fig. 6.

Note that Fig. 6 and Eq. (8) are derived from the hidden failure model in [26] and [27], which is widely used in the study of cascading outages. A hidden failure is undetectable during normal operation but will be exposed as a direct consequence of other system disturbances, which might cause a relay system to incorrectly and inappropriately disconnect circuit elements. Line protection hidden failures are incorporated here in the simulation to model the operation of protective relays. Each line has a different load dependent probability of incorrect trip that is modeled as an increasing function of the line load flow seen by the line protective relay. The probability is low below the line limit, and increases linearly to 1 when the line flow is 1.4 times the line limit.

In (7), K_l is the expected value of the number of outages propagated through inter-regional link l based on IRIG; $f(P_i)$ reflects the probability that link l may be activated under the current operating load state. Therefore, the proposed index $P_{\text{int},l}$ comprehensively considers the statistical analysis results and actual operating status, which is suitable for online analysis of the importance of links. The larger the $P_{\text{int},l}$, the more serious the consequences of inter-regional cascading outages.

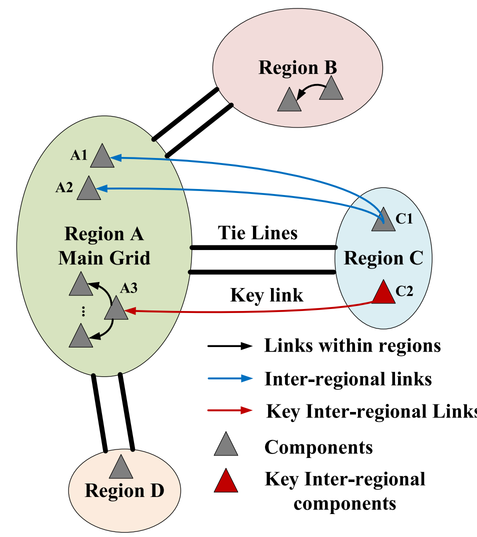

Fig. 7. Schematic diagram of mitigation control.

IV. The Proposed Mitigation Control Scheme

A. Identification of Key Inter-Regional Links and Components

To isolate cascading outages in a local region, the control target should be a set of propagation paths on the IRIG. An easy way is to select the inter-regional links since they can just split the IRIG as needed. Fig. 7 gives the schematic diagram of the proposed mitigation control method.

In this interconnected grid, there are four regions, i.e., Region A, Region B, Region C, and Region D. Assume that Region C is the initial region and the remaining regions constitute the outer region. The mitigation control target can be the set of the inter-regional links, i.e., {(C1→A1), (C1→A2), (C2→A3)}, which is different from the tie lines. In this figure, there are only three inter-regional links which is not very hard to be blocked. However, in some circumstances, there may be a large number of inter-regional links, and most of them have low probabilities. Under these circumstances, blocking all the inter-regional links will be inefficient and difficult. Thus, we can rank the inter-regional links by index $P_{\text{int},l}$ and only block the top-ranked ones.

Key inter-regional links are those with large $P_{\text{int},l}$. An index S_i is defined to assess the risk of the outage of component i. Since there may be multiple links starting from node i, S_i can be expressed as

$$S_i = \sum_{l \in L^{\text{out}}} P_{\text{int},l} \tag{9}$$

where L^{out} is the set of links starting from vertex i. Thus, key inter-regional components are those highly ranked by S_i of a selected number.

Although the control targets are inter-regional links on the IRIG, the control measures still need to be implemented in the physical power grid. Specifically, the control measures should be applied to the components, i.e., blocking the inter-regional links by preventing the starting vertex (component) from outages.

Consider from the practical aspect, preventing all the starting vertexes (components) from outage is inefficient.

Here, we construct a criterion to determine the control target, which can be expressed as follows:

$$S_i > S_{\text{set}} \tag{10}$$

where S_{set} is a risk threshold.

The physical meaning is to preventing component i from outage when index S_i exceeding a certain risk threshold.

Note that for a probabilistic criterion, the core is how to choose the risk threshold. If the threshold is too low, it will cause frequent actions of mitigation control and cause unnecessary losses. If the threshold is too high, it will increase the risk of inter-regional cascading outages, which may lead to severe consequences. A reasonable risk threshold needs to be determined through continuous research and experimentation.

B. Sensitivity Based Load Shedding Strategy

There are many ways to lower the outage rate of target components, and an easy and common way is reducing their load rate. In practice, there are many ways to reduce the load rate of the components, such as load shedding and generation re-dispatch, which is an independent important research topic. In this paper, we employ a simple load shedding method proposed in [28] to achieve the control purpose, more practical schemes for eliminating overload are also applicable and can be found in other specialized literature.

Suppose the load powers have constant power factors. Then the sensitivity relationship between the control target and load powers can be given by (11)

$$\Delta S_x = \sum_j H^m_{x,j} \Delta S_{Lj} \tag{11}$$

where ΔS_x is the change in the apparent power flow on control target *x*; ΔS_{Lj} represent the amount of load shed at bus *j*; $H^m_{x,j}$ is the sensitivity of power flow on the control target to the apparent load power.

By sensitivity analysis, the effective load shedding locations with the larger sensitivities will be selected. In order to ensure that the flow of the control target after load shedding can be lower than the line limit, set 5% power flow margin. Then the expected flow reduction $\Delta S_{x,\text{exp}}$ can be given by (12), where S_x and $S_{x,\text{lim}}$ are the power flow and line limit of control target, respectively. The achieved reduction $\Delta S_{x,*}$ can be calculated by (13), where $\Delta S_{Lj} = \alpha_j \times S_{Lj}$, α_j is the shedding fraction of the selected load, *n* and *k* are the numbers of total loads and selected loads, respectively. The $\Delta S_{x,*}$ must exceeds $\Delta S_{x,\text{exp}}$ which proves the emergent state has been prevented successfully.

$$\Delta S_{x,\text{exp}} = (1 + 5\%) \times (S_x - S_{x,\text{lim}}) \tag{12}$$

$$\Delta S_{x,*} = \sum_{j=1}^{k} H^m_{x,j} \times \Delta S_{Lj} = \sum_{j=1}^{k} H^m_{x,j} S_{Lj} \times \alpha_j \;\; k \leq n \tag{13}$$

If the load shedding amount on the *m* selected loads has the same step size, namely $\alpha_1 = \alpha_2 = \ldots = \alpha_j = \alpha$, then the amount

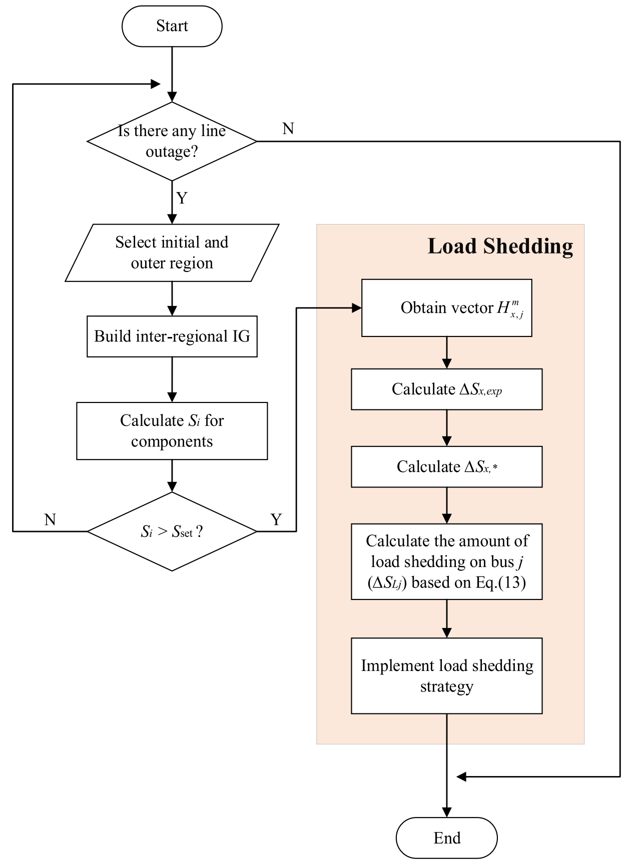

Fig. 8. The flowchart of the proposed mitigation control scheme.

of load shedding can be obtained by (14):

$$\alpha = \frac{\Delta S_{x,\text{exp}}}{\sum_{j=1}^{k} H^m_{x,j} S_{Lj}} \tag{14}$$

Fig. 8 presents the flowchart of the proposed mitigation control scheme, and it performs the following steps:

Algorithm: Mitigation Control Based on IRIG.

Step 1. If detect line outages, start the program. Otherwise end this loop.
Step 2. Select the initial region $\boldsymbol{R}_{ini}$ and outer region $\boldsymbol{R}_{\text{out}}$.
Step 3. Build the IRIG with Section II.
Step 4. Calculate S_i for overload components with (6)–(9).
Step 5. If $S_i > S_{\text{set}}$, implement load shedding strategy and end the program. Otherwise jump to **Step 1**.

V. Case Study

A. Building the IRIG

The proposed mitigation scheme is firstly tested on the IEEE 118-bus test system using the hidden failure model in MATLAB 2020 environment. The grid model is static model with AC

TABLE I
THE TARGET AND OUTER REGIONS

	Included buses	Number of buses
Initial region	[68:112], [115:118]	49
Outer-region	[1:67], [113], [114]	69

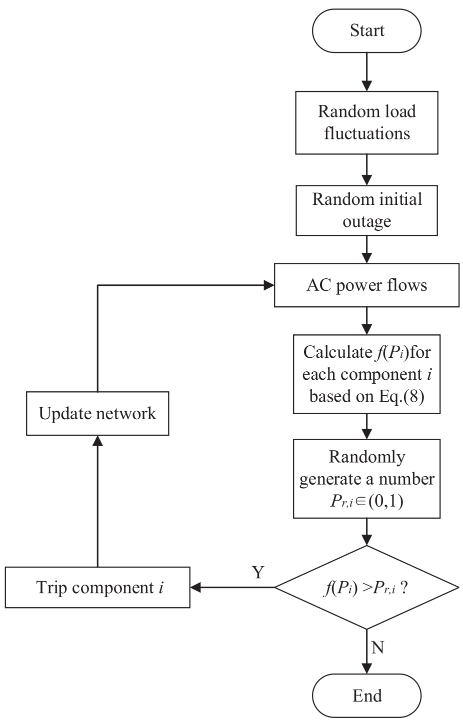

Fig. 9. Flowchart for generating the database.

TABLE II
KEY INTER-REGIONAL COMPONENTS

	Key Component	S_i
1	(69-75)	35.51
2	(69-70)	6.24
3	(80-96)	0.14
4	(103-105)	0.13
5	(89-92)	0.11

power flows. The mis-operation probability p in (8) is set to be 0.001 [26]. Assume that the initial region, and outer region are divided based on Table I. The initial faults (N-2) start in the initial region and we want to prevent the outer region from the influence of the initial region. Generate a database with 10,000 cascades using the hidden failure model and build the IRIG based on Section II. The flowchart for generating the database is shown in Fig. 9.

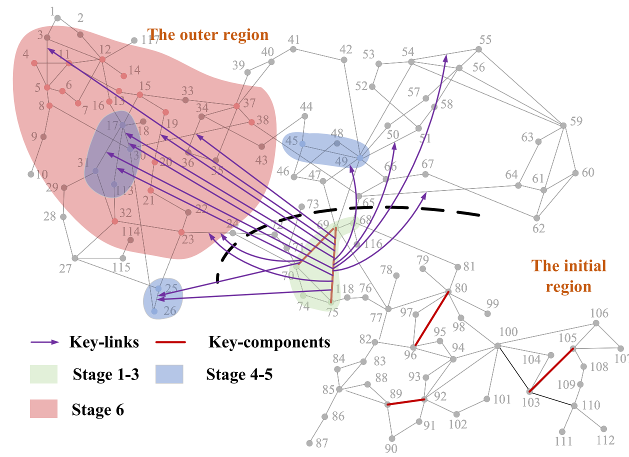

Fig. 10. A propagation process of a cascading outages case.

The process of generating the database is given as follows:

Algorithm: Generating the Database.

Step 1. Initialize load and N-2 fault. Assuming that the load carried by the node has random fluctuations between positive and negative 20%, the initial fault is N-2 faults in the initial region.
Step 2. Calculate AC power flows.
Step 3. Calculate $f(P_i)$ for each component i based on Eq. (8).
Step 4. Generate a number $P_{r,i} \in (0, 1)$ randomly.
Step 5. If $f(P_i) > P_{r,i}$, trip component i and update the network, return to **Step 2**. Otherwise, end the simulation.

B. A Specific Example

Fig. 10 illustrates a typical propagation process of a cascading outages case without any mitigation strategy. In this case, the initial faults are line (68-69) and line (70-74) outages. In the early stages 1-3, the fault is limited to a small region (green shaded region) of the initial region, and then it propagated to the outer region (stage 4 and stage 5, blue shaded region). Finally, the outages spread to the entire left half of the outer region and caused a large-scale blackout (stage 6, red shaded region). This case is representative and matches with the development of many actual cascading blackouts.

1) Identification of Key Inter-Regional Links and Components: Identify the key links and key components and show them in Tables II and III, respectively. Link (A, B) → (C, D) represents the link from component (A-B) to component (C-D). All the key links (purple arrows) and key components (red line) are drawn in Fig. 10. It can be seen that almost all the key links start from component (69-75).

TABLE III
KEY INTER-REGIONAL LINKS

	From component		To component	$P_{\text{int},l}$
1	(69-75)	→	(26-25)	19.78
2	(69-75)	→	(23-24)	9.23
3	(69-70)	→	(26-25)	5.39
4	(69-75)	→	(30-17)	2.53
5	(69-75)	→	(47-49)	1.47
6	(69-70)	→	(23-24)	0.35
7	(69-75)	→	(17-31)	0.32
8	(69-75)	→	(19-20)	0.27
9	(69-75)	→	(17-113)	0.24
10	(69-70)	→	(30-17)	0.19
11	(69-75)	→	(64-65)	0.09
12	(69-75)	→	(49-51)	0.07
13	(69-75)	→	(54-55)	0.06
14	(69-75)	→	(34-36)	0.05
15	(69-75)	→	(3-5)	0.05

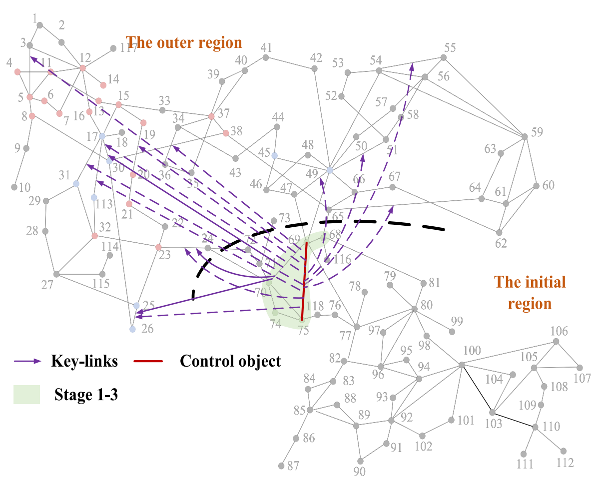

Fig. 11. The propagation process when implementing mitigation control.

2) Implementation of Mitigation Control: When S_{set} is set to be 10. the control target is line (69,75) at stage 2. Shed bus 74 2.0 MVA load.

The cascading propagation process when implementing the proposed mitigation scheme is shown in Fig. 11. The purple dashed arrows illustrate the broken inter-regional linkages in the IRIG. The comparison results of implementing mitigation control and not taking any mitigation measure are shown in Table IV. It can be seen that under the circumstance of implementing mitigation scheme, the cascading outages can be successfully isolated within the initial region in an early stage. The total number of line outages dropped from 28 to 2, and the blackout in the outer region can be effectively avoided.

C. Statistical Analysis

To further verify the effectiveness of the proposed mitigation scheme. It is necessary to perform statistical analysis on the

TABLE IV
THE COMPARISON RESULTS OF IMPLEMENT MITIGATION AND NO MITIGATION

Stage	No mitigation		Flexible islanding	
	Target	Outer	Target	Outer
1	2	0	2	0
2	1, *line(69-75)*	0	stop	-
3	1, *line(69-70)*	0	-	-
4	0	2	-	-
5	0	3	-	-
6	1	18	-	-
Total	5	23	2	0

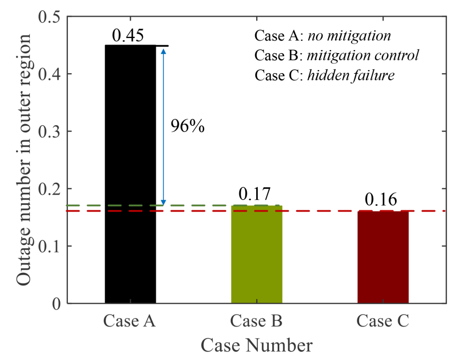

Fig. 12. Average number of outages in the outer region.

control results in a large number of scenarios. Here, we generate three different databases to compare and analyze the control effect of the proposed mitigation scheme. The characteristics and uses of each database are as follows:

Database A: An initial fault (N-2) happened in the initial region; the operators do not implement any mitigation strategy; Generate 10,000 cases based on the hidden failure model. The statistical result is remarked as *no-mitigation*.

Database B: An initial fault (N-2) happened in the initial region; the operators implement the proposed mitigation scheme when needed; Generate 10,000 cases based on the hidden failure model. The statistical result is remarked as *mitigation control*.

Database C: There is no initial fault, and the operators do not implement any mitigate strategy. Generate 10,000 cases based on the hidden failure model. This database is used to statistic the outages caused by hidden failure itself, which is remarked as *hidden failure*.

The statistical analysis results of the outages in the outer region are shown in Fig. 12.

Due to the hypothesis of hidden failure, there are two causes of the outages in the outer region, i.e., triggered by the influence from the initial region or triggered by the hidden failure of the outer region itself. To be able to fairly and objectively evaluate the control effect of the proposed control scheme, we eliminate the influence of outer region itself by subtracting the value of Case C (0.16) from Case A (0.45) and Case B (0.17). Then, the outages in the outer region of *mitigation control* reduced

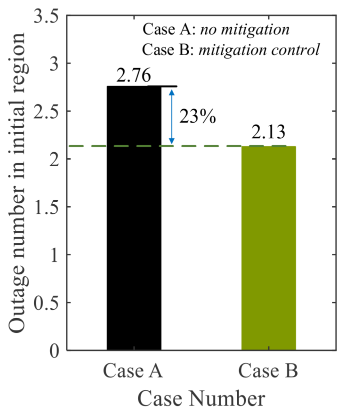

Fig. 13. Average number of outages in the initial region.

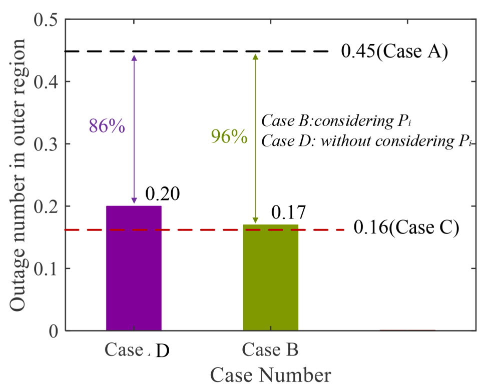

Fig. 14. The comparison results between with and without considering power flow.

by 96% compared with *no-mitigation*. This result verified the effectiveness of the proposed mitigation control scheme.

We also analyzed the statistical results of the initial region and shown them in Fig. 13. Compared with *no-mitigation*, the average number of outages of *mitigation control* was reduced by 23%. It means that the initial region also benefits from the proposed mitigation strategy. Since in many cases, the inter-regional key components are also critical in the initial region.

Moreover, a new database D is generated to compare the differences between with and without considering power flow P_i, and the comparison results are shown in Fig. 14.

Database D: An initial fault (N-2) happened in the initial region; the operators implement the proposed mitigation scheme without considering the power flow P_i; Generate 10,000 cases based on the hidden failure model. The statistical result is remarked as *without considering* P_i.

The results show that the number of outages in the outer region of Case B (considering power flow P_i) has a 10% lower compared to Case D (without considering power flow P_i). Therefore, considering the influence of power flow in the algorithm can improve the control effect of the proposed mitigation strategy.

D. Test on Actual Grid Model

To further demonstrate the performance, the proposed scheme is tested on an actual early planning grid model. This test model is based on an early interconnected grid model including the Southwest China Grid, Central China Grid and East China Grid. This model contains multiple UHV AC/DC transmission lines, considering various power devices. The simulation platform uses the PSD-BPA program developed by the China Electric Power Research Institute, widely used in practical projects throughout China. All generators, line models, and various parameters come from actual engineering. The generation process of the database is the same as in Section V-A. The brief schematic diagram is illustrated in Fig. 15.

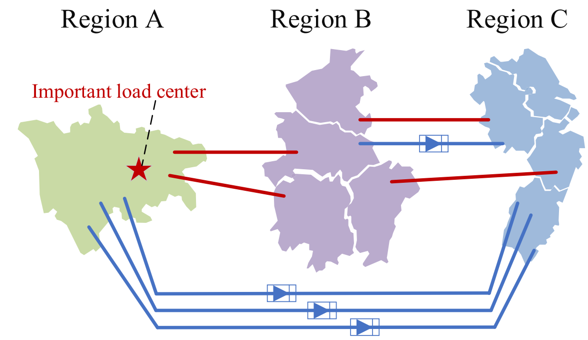

Fig. 15. Schematic diagram of the test interconnected system.

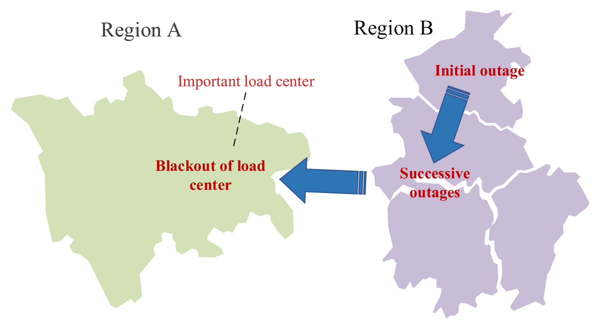

Fig. 16. Typical fault scenario for the test system.

Based on simulation analysis and engineering experience, the typical fault scenario for this system that needs to be focused on is shown in Fig. 16. The faults first occur in Region B, then components successive outages in Region B. Finally, the outages propagate to Region A and cause a blackout of the load center.

To mitigate the mentioned inter-regional cascading outages above and protect the load center in Region A. Choose Region B as the initial region, Region A as the outer region. Assuming that the load in the network fluctuates randomly between 0.8 and 1.2, the initial faults happen in the initial region due to load changing and hidden failure. Generate a database with 10,000 cascades using the test model and build the IRIG based on Section II. The key inter-regional links are given in Table V and shown in Fig. 17.

In Fig. 17, all the top-ranked key inter-regional links are pointed to the load center in Region A, which is consistent with the typical fault scenario found by simulation analysis. Use the proposed mitigation scheme to breaking inter-regional linkages. The results are shown in Figs. 18 and 16.

TABLE V
KEY INTER-REGIONAL LINKS

	From component		To component	$P_{\mathrm{int},l}$
1	(192,193)	→	(223,225)	280
2	(194,191)	→	(217,230)	95.3
3	(199,200)	→	(223,225)	25.1
4	(199,200)	→	(226,224)	9.65
5	(191,202)	→	(223,225)	5.01
6	(222,195)	→	(223,225)	5.01
7	(193,205)	→	(223,225)	5.00
8	(194,191)	→	(224,225)	4.76
9	(199,200)	→	(224,225)	3.57
10	(194,191)	→	(226,224)	3.22

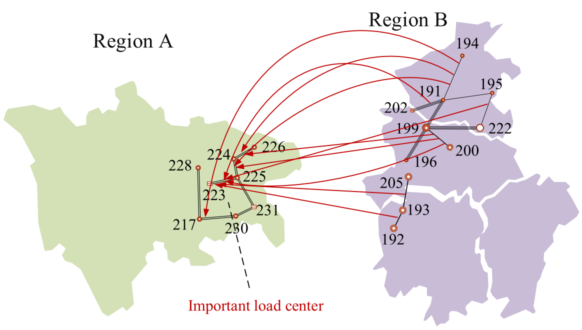

Fig. 17. Key inter-regional links.

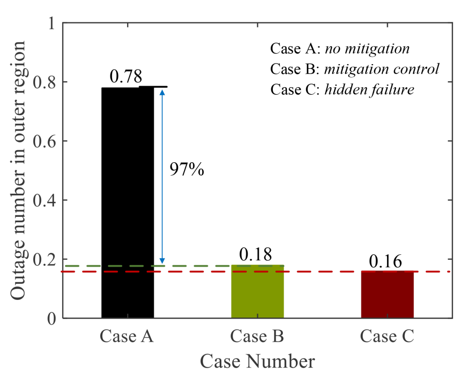

Fig. 18. Average number of outages in the outer region.

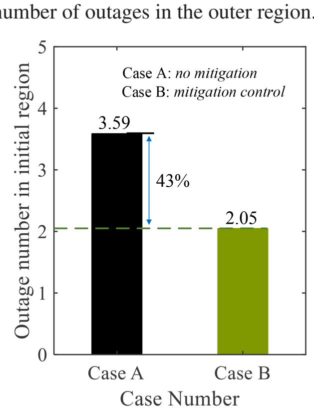

Fig. 19. Average number of outages in the initial region.

Compared with *no-mitigation*, the average number of outages in the outer region of *mitigation control* was reduced by 97%. The average number of outages in the initial region of *mitigation control* was reduced by 43%. These results prove the adaptability of the proposed mitigation scheme in the actual power grid model.

VI. CONCLUSION

The mitigation of cascading failures is a highly complex problem. Simplifying the problem's difficulty and making it easier to realize is essential to the practical application of mitigation methods. This paper proposes a scheme to simplify the problem by focusing on breaking inter-regional linkages of component failures. The conclusions of this paper are as follows:

1) The proposed IRIG can significantly reduce the complexity of the original IG.
2) The proposed mitigation strategy based on inter-regional IG can effectively mitigate cascading outages across regions.
3) In most cases, the proposed mitigation scheme also reduced the outages in the initial region since the inter-regional key components are also critical for the initial region.
4) The degree of simplification of the IRIG is related to the way of regional division. At present, it can be adopted according to the grid structure and engineering experience. A better division method will be a complex optimization problem, which will be studied in the future.

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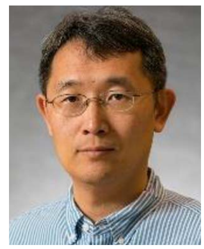

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