Abstract—Cascading failures triggered by trivial initial events are encountered in many complex systems. It is actually not any specific reason but the interaction between components of the system that causes cascading failures. Based on this idea interactions between components are quantified and the interaction matrix and interaction network are obtained. By using the quantified interactions, key links and key components that play important roles in the propagation of cascading failures are identified. An interaction model is also proposed to simulate cascading failures by using the interactions and to study the influence of these interactions on the cascading failure risk. Interaction-based mitigation measures are suggested to mitigate the cascading failure risk by eliminating a small number of key links, which can be achieved in real systems by wide area protection such as blocking of some specific protective relays. The proposed interaction quantifying method, cascading failure model, and mitigation measures are validated with line outage data generated by the AC OPA cascading simulations on the IEEE 118-bus system.

Index Terms—Blackout, cascading failure, interaction, mitigation, network, power transmission reliability, relay, simulation, wide area protection and control.

I. INTRODUCTION

Cascading blackouts are complicated sequences of dependent outages which could bring about tremendous economic and social losses [1], [2]. It is important to study the mechanisms of cascading failures so that the risk of large-scale blackouts may be better quantified and mitigated.

In order to study cascading failures, several models have been proposed, such as CASCADE model [3], branching process model [4]–[6], hidden failure model [7], [8], OPA model [9]–[12], AC OPA model [13], [14], OPA with slow process [15], Manchester model [16], [17], stochastic model [18], dynamic PRA model [19], and influence model [20].

The branching process model [4]–[6] can provide higher-level statistical information about cascading failures by tracking the numbers of lines outaged and amounts of load shed. But it does not retain information about the network topology or load flow and does not attempt to specify how cascades propagate in the system in detail. The most recent study on the line interaction graph [21] initiates a novel analysis method for cascading failures by considering the interactions of transmission lines and tries to understand cascading failures with models amenable to analysis while keeping the basic physics of power systems.

From the perspective of complex systems the system-level failures are not caused by any specific reason but by the property that the components are tightly coupled and interdependent [22]. Thus explicitly studying the interactions between components can help understand the mechanisms of cascading failures, identify the key factors for their propagation, and further propose effective mitigation measures.

In this paper we quantify the interactions between components by following the line graph approach in [21]. These interactions can help identify key links between components which plays crucial roles in the propagation of cascading failures and thus are useful for determining wide area protection schemes [23], [24], such as relay blocking under the condition of some specific line tripping, which can secure time to perform remedial controls by a defense system during cascaded events [25]. A cascading failure model is further proposed based on these interactions to study how component interactions influence cascading failure risks.

Besides, topological properties such as small-world [26] and scale-free [27] behaviors have been found in complex networks. But it can be misleading to evaluate the vulnerability of power systems only with topological metrics [28]. In this paper we discuss the property of a directed weighted interaction network generated with simulated cascades from a more detailed blackout model that considers the physics of the system such as power flow and re-dispatching.

The rest of this paper is organized as follows. Section II explains the interaction quantifying method. Section III discusses the identification of key links and key components based on the obtained interactions. Section IV proposes an interaction model by using the interactions between components and discusses methods for validating it. Section V discusses mitigation measures by eliminating key links. Section VI tests the proposed method with line outage data generated by AC OPA simulations on IEEE 118-bus system. Finally the conclusion is drawn in Section VII.

II. QUANTIFYING INTERACTIONS BETWEEN COMPONENTS

In this section a method to quantify the interactions between components is proposed by using cascades that record cascading failure sequences.

For power systems the transmission lines or transformers can be chosen as components and the cascades can come from statistical line outage data or simulations generated from OPA model or its variants. The statistical data can be grouped into different cascades and then into different generations within each cascade based on outages’ timing [3]. The simulation
of OPA and its variants can naturally produce line outages in generations or stages; each iteration of the main loop of the simulation produces another generation [1], [3].

The cascades used for quantifying component interactions are called original cascades in order to distinguish the simulated cascades from the proposed model in this paper. Original cascades can be arranged as

| generation 0 | generation 1 | generation 2 | ... |
|--------------|--------------|--------------|-----|
| cascade 1   | $F_0^{(1)}$  | $F_1^{(1)}$  | $F_2^{(1)}$ | ... |
| cascade 2   | $F_0^{(2)}$  | $F_1^{(2)}$  | $F_2^{(2)}$ | ... |
| ...         | ...          | ...          | ...         | ... |
| cascade $M$ | $F_0^{(M)}$  | $F_1^{(M)}$  | $F_2^{(M)}$ | ... |

where $F_j^{(m)}$ is the set of failed components produced in generation $j$ of cascade $m$. Each cascade eventually terminates with a finite number of generations when the number of failed components in a generation becomes zero.

It is first assumed that there are interactions between any failed component in last generation and that in this generation. Thus for a system with $n$ components, a matrix $A \in \mathbb{Z}^{n \times n}$ can be constructed, whose entry $a_{ij}$ is the number of times that component $i$ fails in one generation before the failure of component $j$ among all original cascades.

The assumption based on which $A$ is obtained actually exaggerates the interactions between components since it is not convincing to assert one component interacts with another one only because it fails in its last generation. Therefore, for each failed component in generation one and the following generations the failed component that most probably causes it should be determined.

Specifically, the failure of component $j$ is considered to be caused by the failed component with the greatest $a_{ij}$ among all component failures in the last generation. If there are more than one component have the same greatest $a_{ij}$ all of them will be considered as the cause of the failure of component $j$. Then $A$ can be corrected to be $A' \in \mathbb{Z}^{n \times n}$, whose entry $a'_{ij}$ is the number of times that the failure of component $i$ causes the failure of component $j$.

The interaction matrix $B \in \mathbb{R}^{n \times n}$ can be calculated from $A'$. Its entry $b_{ij}$ is the empirical probability that the failure of component $i$ causes the failure of component $j$. From the Bayes’ theorem

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

where $N_i$ is the number of failures of component $i$.

The $B$ matrix actually determines how components interact with each other. The nonzero elements of $B$ are called links. Link $l : i \rightarrow j$ corresponds to $B$’s nonzero element $b_{ij}$ and starts from component $i$ and ends with component $j$. By putting all links together a directed network called the interaction network can be obtained. Its vertices are components and each directed link represents that a failure of the source vertex component causes the failure of the destination vertex component with probability greater than 0.

III. IDENTIFYING KEY LINKS AND KEY COMPONENTS

The links can vary significantly with respect to their roles in the propagation of cascading failures. In order to distinguish them and to further identify key links, an index $I_l$ is defined for each link $l : i \rightarrow j$ to be the expected number of failures link $l$ can cause given $N_i$, which is the number of failures of its source vertex $i$ and can be obtained from the original cascades.

The expected failures of component $j$ is

$$E_j = N_i b_{ij}$$

Then the expected number of failures caused by the failure of component $j$ is

$$E_j \sum_{k \in j} b_{jk}$$

where $k \in j$ denotes the destination vertices starting from $j$.

This continues until reaching the vertices without outgoing links. All the expected failures are summed to be $I_j$. In fact,

$$I_j = \sum_{v \in V} E_v$$

where $V$ is the set of vertices for which there exists a path starting from link $l$ and $E_v$ is the expected number of failures of vertex $v$.

$I_l$ can indicate the contribution of a link to the propagation of cascading failures. The greater the index is, the more important the link is for cascading failure propagation. Thus the links with large $I_l$ can be defined as key links. Specifically, the set of key links $L^{key}$ are those links whose weights are greater than or equal to a specified fraction of the largest link weight $I_l^{max}$, that is

$$L^{key} = \{ l | I_l \geq \epsilon_l I_l^{max} \}$$

where $\epsilon_l$ is taken as a value that is not too close to zero to guarantee that the weights of key links are not much less than the largest link weight.

Taking $I_l$ as weights of the links, a directed weighted network called interaction network can be obtained. The vertex out-strength and in-strength can be defined as follows.

$$s_{i}^{out} = \sum_{l \in L^{out}(i)} I_l$$
$$s_{i}^{in} = \sum_{l \in L^{in}(i)} I_l$$

where $L^{out}(i)$ and $L^{in}(i)$ are respectively the sets of links starting from and ending with vertex $i$.

The out-strength and in-strength can indicate how much an component influences and is influenced by another one. The components with large out-strength can cause great consequences and thus are crucial for the propagation of cascading failures. Therefore, in a similar way to the key link definition, the set of key components $C^{key}$ is defined as:

$$C^{key} = \{ i | s_{i}^{out} \geq \epsilon_s s_{i}^{out,max} \}$$

where $s_{i}^{out,max}$ is the largest out-strength among all vertexes and $\epsilon_s$ is used to guarantee that the out-strengths of key components are not much less than the maximum out-strength.
IV. Interaction Model

In this section a cascading failure model called interaction model is proposed by considering the interactions between components and the validation of this model is also discussed.

A. Model Design

It is assumed that initially all components work well and the cascading failure process is triggered by a small fraction of component failures. The component failures in the same generation cause other component failures independently. The flow chart of the proposed model is shown in Fig. 1.

![Flow chart of the interaction model](image)

Fig. 1. Flow chart of the interaction model.

The model contains two loops and in each outer loop a cascade is simulated. Specifically, the model is implemented in the following 3 steps.

Step 1) Accidental faults of lines
In the 0th outer iteration, each line is tripped with probability \( \tau \) to simulate accidental faults.

Step 2) Corresponding columns are set zero
The columns of \( B \) corresponding to the component failures are set zero since in our model once a component fails it will remain that way until the end of the simulation.

Step 3) Failed components cause other component failures
The component failures in one generation independently generate other component failures. Specifically, if component \( i \) fails in this generation it will cause the failure of any other component \( j \) with probability \( b_{ij} \). Once it causes the failures of some components, these newly caused component failures will comprise the next generation; then go back to step 2. If no component failure is caused, the inner loop stops.

Since we want to focus on the interaction of components rather than the triggering events, the component failures in generation 0 (initial outages) of an original cascade are directly considered as generation 0 failures in the simulated cascade.

B. Validating the Model

In order to validate the proposed model, the simulated cascades are carefully compared with the original cascades with the following four methods.

1) The probability distribution of total line outages of the original and simulated cascades are compared.
2) The probability distribution of total line outages of the original and simulated cascades can be estimated with the branching process and the average propagation (estimated offspring mean) \( \lambda \) can be compared. More details can be found in [4] and [6].
3) The interactions between components for both the original and simulated cascades are quantified and the probability distribution of the link weights and vertex out-strength and in-strength of the interaction network are compared.
4) The links of the original and simulated cascades are compared in more details with some defined similarity indices.

Because the first three methods are natural only the fourth one will be discussed in detail. Let \( L_1, L_2, \) and \( L_3 \) be the set of links shared by the original and simulated cascades and the links only owed by the original and simulated cascades. Denote the index of link \( l \) for the original and simulated cascades respectively by \( I_l^{ori} \) and \( I_l^{sim} \). Five similarity indices are defined as follows.

\[
S_1 = \frac{\sum_{l \in (L_1 \cup L_2)} I_l^{sim}}{\sum_{l \in (L_1 \cup L_2)} I_l^{ori}}
\]

(9)

\[
S_2 = \frac{\sum_{l \in L_1} I_l^{ori}}{\sum_{l \in L_1} I_l^{ori}}
\]

(10)

\[
S_3 = \frac{\sum_{l \in L_1} I_l^{sim}}{\sum_{l \in (L_1 \cup L_3)} I_l^{sim}}
\]

(11)

\[
S_4 = \frac{\sum_{l \in L_1} I_l^{sim}}{\sum_{l \in L_1} I_l^{ori}}
\]

(12)

\[
S_5 = \frac{\sum_{l \in L_1} \left( \frac{I_l^{sim} + I_l^{ori}}{I_l^{ori}} \right)}{\sum_{l \in L_1} \left( \frac{I_l^{sim} + I_l^{ori}}{I_l^{ori}} \right)}
\]

(13)

\( S_1 \) is the ratio between the summation of the link weights of the simulated cascades and that of the original cascades.
If $S_1$ is close to 1.0 the links of the original and simulated cascades have almost the same propagation capacity. $S_2$ and $S_3$ are used to indicate if the shared links play the major role among all links for the original and simulated cascades. If they are near 1.0 it means that the shared links dominate and thus the simulated cascades are similar to the original cascades.

$S_4$ indicate the similarity between the overall propagation capacity of the shared links of the simulated cascades and that of the original cascades. $S_4 \approx 1$ will suggest that the overall propagation capacity of the shared links for the simulated cascades are close to that of the original cascades.

But even when $S_4 \approx 1$ it is still possible that the weight of the same link for the original and simulated cascades can be quite different. Thus $S_5$ is defined to show if the same link is close to each other. When $S_5$ is near 1.0 it indicates that at least the most important links of the simulated cascades have propagation capacity close to their counterparts for the original cascades.

V. CASCADING FAILURE MITIGATION MEASURES

Since the interaction of components is the true reason that causes the system-level failures of a complex system, one possible mitigation measure can be performed by eliminating some key links between components, which will possibly stop the propagation of cascading failures.

After validating the proposed interaction model in section IV, this model can be applied to study how the interactions between components influence the cascading failure risk and to validate the effectiveness of the mitigation measures based on the elimination of key links. In real systems the elimination of key links can be implemented by blocking some specific protective relays. The zone 3 relay blocking method called adaptive distance relay scheme has been discussed in [25]. In this paper relays are blocked under the condition of the tripping of the lines corresponding to the source vertexes of the key links. Since the key links can cause tremendous expected number of failures and thus play crucial roles in the propagation of cascading failures it should be beneficial to the overall security of the system to stop the propagation from the source vertexes of key links to the destination vertexes by blocking the operation of the relay of the destination vertexes, thus securing time for the operators to take remedial actions, such as re-dispatching the generation or even shedding some loads, and finally helping mitigate catastrophic failures.

This relay blocking strategy under the condition of some specific line tripping can be considered as a wide area protection scheme, which can be simulated in AC OPA model by adding a relay blocking module. When the line corresponding to the source vertex of a key link is tripped and further causes the overloading of the line corresponding to its destination vertex, the destination vertex line will not be tripped to simulate the blocking of its relay and AC OPA will go to its next inner iteration, in which AC OPF will be calculated and generation re-dispatching and load shedding will be performed to eliminate the overloading of the destination vertex line.

VI. RESULTS

This section presents results for interaction matrix, interaction network, and interaction model. The cascading outage data is produced by open-loop AC OPA simulation [13], [14] on IEEE 118-bus system, which is standard except that the line flow limits are determined with the same method in [6]. The probability for initial line outage is $p_0 = 0.0001$ and the load variability $\gamma = 1.67$, which are the same as [4].

For testing the interaction quantifying method and the proposed interaction model, AC OPA simulation at base case load level is run so as to produce 5000 cascading outages with a nonzero number of line outages.

A. Interaction Matrix and Interaction Network

There are 186 lines in IEEE 118-bus system and thus $B$ is a $186 \times 186$ square matrix. Table I shows the number of components $n$, the number of $B$’s nonzero elements $N$, which is also the number of links, and the ratio of nonzero elements $r = N/n^2$. It is seen that $r$ is very small, indicating that the interaction matrix is very sparse and that only a small fraction of lines interact with each other.

| TABLE I | NONZERO ELEMENTS IN B FOR IEEE 118-BUS SYSTEM |
|---------|-----------------------------------------------|
| system  | model | n  | N     | r     |
| IEEE 118| AC OPA| 186| 202 | 0.00584 |

The corresponding directed weighted interaction network is shown in Fig. 2 in which the dots denote lines in IEEE 118-bus system and the arrows denote the links between lines. Here we do not show the weights of the links but only the topology of the interaction network. This network is different from the one-line diagram of IEEE 118-bus system, for which the vertexes are buses and the undirected links between vertexes are lines.

![Fig. 2. Interaction network for IEEE 118-bus system.](image)

B. Key Link and Key Component Identification

In this section key links and key components that play important roles in the propagation of cascading failures are identified by using the method in section III. Both $\epsilon_1$ and $\epsilon_s$ are chosen as 0.15. The identified key links, which are actually line pairs in IEEE 118-bus system, and their weights $I_t$ are listed in Table [II]. The number of key links are only 7.43% of
all the links but the summation of their weights accounts for 84.11% of the total weights of all links.

### Table II

| Key Link | Line Pairs | \( I \) |
|----------|------------|--------|
| 98       | 74 \(\rightarrow\) 72 | (53, 54) \(\rightarrow\) (51, 52) | 1524 |
| 99       | 74 \(\rightarrow\) 73 | (53, 54) \(\rightarrow\) (52, 53) | 1521 |
| 31       | 40 \(\rightarrow\) 34 | (29, 31) \(\rightarrow\) (27, 28) | 1380 |
| 32       | 40 \(\rightarrow\) 35 | (29, 31) \(\rightarrow\) (28, 29) | 1329 |
| 101      | 74 \(\rightarrow\) 82 | (53, 54) \(\rightarrow\) (56, 58) | 1307 |
| 73       | 62 \(\rightarrow\) 68 | (45, 46) \(\rightarrow\) (45, 49) | 1235 |
| 158      | 121 \(\rightarrow\) 122 | (77, 78) \(\rightarrow\) (78, 79) | 1191 |
| 159      | 121 \(\rightarrow\) 125 | (77, 78) \(\rightarrow\) (79, 80) | 1191 |
| 40       | 40 \(\rightarrow\) 182 | (29, 31) \(\rightarrow\) (114, 115) | 810 |
| 46       | 46 \(\rightarrow\) 47 | (35, 36) \(\rightarrow\) (35, 37) | 686 |
| 1        | 12 \(\rightarrow\) 18 | (11, 12) \(\rightarrow\) (13, 15) | 615 |
| 33       | 40 \(\rightarrow\) 43 | (29, 31) \(\rightarrow\) (27, 32) | 564 |
| 78       | 68 \(\rightarrow\) 59 | (45, 49) \(\rightarrow\) (43, 44) | 458 |
| 139      | 102 \(\rightarrow\) 74 | (65, 66) \(\rightarrow\) (53, 54) | 385 |
| 135      | 102 \(\rightarrow\) 40 | (65, 66) \(\rightarrow\) (29, 31) | 287 |

The identified key components, the corresponding lines, and their out-strengths are listed in Table III. The tripping of these lines will cause severe consequences and thus should be prevented to the greatest extent. For IEEE 118-bus system there are a total of 186 components and among them 72 components are involved in the original cascades. The number of key components are 3.76% of all components and 9.72% of the involved components. The summation of the out-strengths of the key components accounts for 88.74% of the total out-strengths of the involved components.

### Table III

| Key Component | Line | \( \omega^{\text{out}} \) |
|---------------|------|------------------|
| 74            | (53, 54) | 4590            |
| 40            | (29, 31) | 4103            |
| 121           | (77, 78) | 2389            |
| 62            | (45, 46) | 1240            |
| 102           | (65, 66) | 1220            |
| 46            | (35, 36) | 959             |
| 68            | (45, 49) | 778             |

The identified key links and key components are denoted on the one-line diagram of IEEE 118-bus system, which is shown in Fig. 3. It is seen that the lines corresponding to the source and destination vertexes of some key links can be topologically far away from each other, such as link 139 : (65, 66) \(\rightarrow\) (53, 54) and 135 : (65, 66) \(\rightarrow\) (29, 31), although for most key links the source and destination vertexes are lines that are topologically close to each other, such as link 98 : (53, 54) \(\rightarrow\) (51, 52) and 99 : (53, 54) \(\rightarrow\) (52, 53). This is because the interactions and links are obtained from simulated cascades generated by AC OPA model which not only considers the topology of the power network but also other physics of the system, such as power flow and the operator response. These factors can also make some components tightly coupled.

C. Model Validation

In this section the proposed interaction model is validated with the four methods discussed in section IV-B. The probability distributions of the total number of line outages for original cascades (plus sign) and simulated cascades (times sign) are shown in Fig. 4.

It is seen that the distributions of total line outages of the original and simulated cascades match well. This suggests that the proposed interaction model can generate cascades with similar statistical properties to the original cascades. The dramatic difference between the distributions of the initial and total outages also suggest that the cascading failure is able to propagate a lot. This is because of the interaction between components denoted by the sparse interaction matrix. If all elements of \( \mathbf{B} \) are zero and the components do not interact at all, all cascades will stop immediately after initial line outages and the distribution of the total line outages will be the same as
initial line outages. Thus, although being sparse, the interaction matrix does take effect.

To quantitatively compare the original cascades and the simulated cascades, the branching process is applied to estimate their average propagation $\lambda$, which are listed in Table IV. It is seen that the average propagation of the simulated cascades are very close to that of the original cascades, indicating that the simulated cascades have similar propagation property to the original cascades.

| model         | $\lambda$ |
|---------------|------------|
| AC OPA        | 0.400      |
| interaction model | 0.402     |

The complementary cumulative distributions (CCD) of the link weights for the original and simulated cascades are shown in Fig. 5. The two distributions match very well. Both of them follow obvious power law and can range from 1 to more than 1000, suggesting that a small number of links can cause much greater consequences than most of the others.

The CCD of the vertex out-strength and in-strength for original and simulated cascades are shown in Figs. 6–7. The strength distributions of the original and simulated cascades match very well, indicating that the simulated cascades share similar features to the original cascades from an overall point of view. An obvious power law behavior can also be seen, which means that the failure of most vertices (components) have small consequences while a small number of them have much greater impact.

The original and simulated cascades separately have 202 and 182 links and they share 132 links. It seems that the simulated cascades are quite different from the original cascades since they have many different links. But when the line weights are taken into account and the five indices defined in section IV-B are calculated, which are listed in Table V it is seen that all five indices are close to 1.0 and thus the links obtained from original and simulated cascades are actually quite similar.

## D. Cascading Failure Mitigation

The key links identified in section VI-B are eliminated by setting the corresponding elements in $B$ matrix to be zero. By doing this we get $B_{\text{int}}$. For comparison the same number of links are also randomly removed, for which $B_{\text{rand}}$ is obtained. Cascading failures are separately simulated with the proposed model by using $B_{\text{int}}$ and $B_{\text{rand}}$. The two mitigation strategies are respectively called intentional mitigation and random mitigation.

Fig. 8 shows the probability distributions of total line outages under the two mitigation strategies. It is seen that the risk of large-scale cascading failures can be significantly mitigated by eliminating only a small number of key links. By contrast, the mitigation effect is minor if the same number of links are randomly removed.

This can be explained by the power law distribution of the link weights. Most links have small weights and only a small
number of links have much greater weights. When randomly removing links it is more possible to choose small-weight links and thus the total propagation capacity of the eliminated links for random mitigation can be significantly weaker than that for the intentional mitigation. This is validated by the fact that the summation of the weights of removed links for intentional and random mitigation are separately 14483 and 1923.

To quantitatively compare the effects of different mitigation measures, the branching process is applied to estimate the average propagation of the original and simulated cascades under two mitigation strategies. The estimated parameters are listed in Table VI. It is seen that the average propagation decreases dramatically under intentional mitigation while decreases only a little under random mitigation.

### Table VI

| Model          | Mitigation Strategies | \( \lambda \) |
|----------------|-----------------------|---------------|
| Interaction    | No mitigation         | 0.402         |
| Model          | Intentional           | 0.0595        |
| Interaction    | Random                | 0.365         |

In order to simulate the implementation of the mitigation strategy by eliminating some links in real systems we add a relay blocking module in AC OPA model. For intentional or random mitigation, when the source vertexes of the predetermined links fail and the destination vertexes of corresponding links become overloaded and will be tripped by protective relays, the operation of the relays will be blocked and AC OPA will go to the next inner iteration, in which AC OPF is performed to simulate the re-dispatching of generation and some loads are shed if necessary in order to eliminate the violation of the line limits. In this way the AC OPA simulations can get cascades under mitigation strategies.

In Figs. 9–10 we respectively compare the probability distributions of the total numbers of the line outages for AC OPA model and interaction model under intentional and random mitigation strategies. Under the same kind mitigation strategy both models remove the same links. It is seen that the distributions for both models match very well under the two mitigation strategies.

The branching process is also applied to estimate the average propagation of the AC OPA and interaction model under two mitigation strategies, which are listed in Table VII. The average propagations for two models under a specific mitigation strategy are on the same level and both reflect the tendency that intentional mitigation significantly decreases the cascading failure risk while random mitigation’s effect is not obvious.
Both AC OPA and interaction model are implemented with Matlab and all tests are carried out on a 3.4 GHz Intel(R) Core(TM) based desktop. AC OPA takes over 8 hours to produce 5000 cascading outages with a nonzero number of line outages while the interaction model only needs 2 seconds to get the same number of cascades after obtaining the interaction matrix. Thus the interaction model can generate cascades and study the influence of component interactions on cascading failure risk much more time efficiently while reserving most of the general properties of the cascades.

VII. CONCLUSION

In this paper we quantify the interaction between components and obtain the interaction matrix and interaction network. Key links and components are identified and an interaction model is proposed to simulate cascading failures and study how interactions between components influence cascading failure risk. The interaction quantifying method and interaction model are validated to be able to capture general properties of the original cascades. An obvious power law is found in distributions of the link weights and the vertex out-strength and in-strength, suggesting that a small number of links and components are much more crucial than the others. Cascading failure risks can be greatly mitigated by removing a few key links, which can be implemented by wide area protection that blocks the operation of relays of the lines corresponding to the destination vertexes of key links when the lines corresponding to the source vertexes are tripped.

REFERENCES

[1] U.S.-Canada Power System Outage Task Force, “Final report on the August 14th blackout in the United States and Canada,” Apr. 2004.
[2] IEEE PES CAMS Task Force on Cascading Failure, “Initial review of methods for cascading failure analysis in electric power transmission systems,” IEEE PES General Meeting, Pittsburgh PA USA, Jul. 2008.
[3] I. Dobson, B. A. Carreras, and D. E. Newman, “A loading dependent model of probabilistic cascading failure,” Probability in the Engineering and Informational Sciences, vol. 19, pp. 15–32, Jan. 2005.
[4] I. Dobson, J. Kim, and K. R. Wierzbicki, “Testing branching process estimators of cascading failure with data from a simulation of transmission line outages,” Risk Analysis, vol. 30, pp. 650–662, Apr. 2010
[5] I. Dobson, “Estimating the propagation and extent of cascading line outages from utility data with a branching process,” IEEE Trans. on Power Systems, Vol. 27, pp. 2146–2155, Nov. 2012.
[6] J. Qi, I. Dobson, and S. Mei, “Towards estimating the statistics of simulated cascades of outages with branching processes,” IEEE Trans. on Power Systems, vol. 28, pp. 3410–3419, Aug. 2013.
[7] A. G. Phadke and J. S. Thorp, “Expose hidden failures to prevent cascading outages,” IEEE Comput. Appl. Power, vol. 9, pp. 20–23, 1996.
[8] J. Chen, J. S. Thorp, and I. Dobson, “Cascading dynamics and mitigation assessment in power system disturbances via a hidden failure model,” Int. J. Elect. Power Energy Sys., vol. 27, pp. 318–326, May 2005.
[9] I. Dobson, B. A. Carreras, V. E. Lynch, and D. E. Newman, “An initial model for complex dynamics in electric power system blackouts,” 34th Hawaii Intl. Conference on System Sciences, HI, pp. 710–718, Jan. 2001.
[10] B. A. Carreras, V. E. Lynch, I. Dobson, D. E. Newman, “Critical points and transitions in an electric power transmission model for cascading failure blackouts,” Chaos, vol. 12, pp. 985–994, Dec. 2002.
[11] H. Ren, I. Dobson, and B. A. Carreras, “Long-term effect of the n-1 criterion on cascading line outages in an evolving power transmission grid,” IEEE Trans. on Power Systems, vol. 23, pp. 1217–1225, Aug. 2008.
[12] B. A. Carreras, D. E. Newman, I. Dobson, and N. S. Degala, “Validating OPA with WECC data,” 46th Hawaii Intl. Conference on System Sciences, HI, Jan. 2013.
[13] S. Mei, Yadana, X. Weng, and A. Xue, “Blackout model based on OPF and its self-organized criticality,” Proceedings of the 25th Chinese Control Conference, pp. 7–11, 2006.
[14] S. Mei, Y. Ni, Weng, G. Wang, and S. Wu, “A study of self-organized criticality of power system under cascading failures based on AC-OPA with voltage stability margin,” IEEE Trans. Power Systems, vol. 23, pp. 1719–1726, Nov. 2008.
[15] J. Qi, S. Mei, and F. Liu, “Blackout model considering slow process,” IEEE Trans. on Power Systems, vol. 28, pp. 3274–3282, Aug. 2013.
[16] M. A. Rios, D. S. Kirschen, D. Jawayere, D. P. Nedic, and R. N. Allan, “Value of security: modeling time-dependent phenomena and weather conditions,” IEEE Trans. Power Systems, vol. 17, pp. 543–548, Aug. 2002.
[17] D. S. Kirschen, D. Jawayere, D. P. Nedic, and R. N. Allan, “A probabilistic indicator of system stress,” IEEE Trans. Power Systems, vol. 19, pp. 1650–1657, Aug. 2004.
[18] M. Anghel, K. A. Werley, and A. E. Mottor, “Stochastic model for power grid dynamics,” 40th Hawaii Intl. Conference on System Sciences, Hawaii, HI, Jan. 2007.
[19] P. Heneaux, P. Labeau, and J. Maun, “Blackout probabilistic risk assessment and thermal effects: impacts of changes in generation,” IEEE Trans. Power Systems, vol. 28, pp. 4722–4731, Nov. 2013.
[20] C. Asavathiratham, S. Roy, B. Lesieutre, and G. Verghese, “The influence model,” IEEE Control Systems Magazine, vol. 21, pp. 52–64, Dec. 2001.
[21] P. D. Hines, I. Dobson, E. Cotilla-Sanchez, and M. Eppestein, “‘Dual Graph’ and ‘Random Chemistry’ methods for cascading failure analysis,” 46th Hawaii Intl. Conference on System Sciences, HI, Jan. 2013.
[22] C. Perron, Normal accident: living with high-risk technologies, Princeton University Press, Princeton, 1999.
[23] M. Begovic, D. Novosel, D. Karlsson, C. Henville, and G. Michel, “Wide-Area Protection and Emergency Control,” Proceedings of the IEEE, vol. 93, pp. 876–891, May 2005.
[24] V. Terzija, G. Valverde, D. Cai, P. Regulski, V. Madani, J. Fitch, S. Skok, M. Begovic, and A. Phadke, “Wide-area monitoring, protection, and Control of future electric power networks,” Proceedings of the IEEE, vol. 99, pp. 80–93, Jan. 2011.
[25] S. Lim, C. Liu, S. Lee, M. Choi, and S. Rim, “Blocking of zone 3 relays to prevent cascading events,” IEEE Transactions on Power Systems, vol. 23, pp. 747-754, May 2008.
[26] D. J. Watts and S. H. Strongatz, “Collective dynamics of small-world networks,” Nature, vol. 393, pp. 440–442, Jun. 1998.
[27] R. Albert and A.-L. Barabási, “Emergence of scaling in random networks,” Science, vol. 286, pp. 509–512, Oct. 1999.
[28] P. Hines, E. Cotilla-Sanchez, and S. Blumsack, “Do topological models provide good information about electricity infrastructure vulnerability,” Chaos, vol. 20, 033122, 2010.