Quantifying the Influence of Component Failure Probability on Cascading Blackout Risk

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Abstract—The risk of cascading blackouts greatly relies on failure probabilities of individual components in power grids. To quantify how component failure probability (CFP) influences blackout risk (BR), this paper proposes a sample-induced semianalytic approach to characterize the relationship between CFP and BR. To this end, we first give a generic component failure probability function (CoFPF) to describe CFP with varying parameters or forms. Then, the exact relationship between BR and CoFPFs is built on the abstract Markov-sequence model of cascading outages. Leveraging a set of samples generated by blackout simulations, we further establish a sample-induced semianalytic mapping between the unbiased estimation of BR and CoFPFs. Finally, we derive an efficient algorithm that can directly calculate the unbiased estimation of BR when the CoFPFs change. Since no additional simulations are required, the algorithm is computationally scalable and efficient. Numerical experiments well confirm the theory and the algorithm.

Index Terms—Cascading outage, component failure probability, blackout risk.

NOMENCLATURE

- $k$: Index of components in the system.
- $K$: Universal set of components in the system.
- $k_i$: Total number of components in the system.
- $\varphi_k$: CoFPF of component $k$.
- $s_k$: Working condition of component $k$.
- $\eta_k$: Parameter vector of component $k$.
- $X_j$: State variables at stage $j$.
- $x_j$: Specific system states at stage $j$.
- $X$: State space of $X_j$.
- $Z$: Markov sequence standing for cascading outage.
- $g(Z)$: Joint probability series of $Z$.
- $Z$: State space of $Z$.
- $n$: Total number of cascading stages.
- $z$: A specific cascading outage.
- $Y$: Load shedding of cascading outages.
- $Y_0$: Load shedding level.
- $R_g$: BR with respect to $g(Z)$.
- $Z_g$: Sample set of cascading outages with respect to $g(Z)$.
- $Y_g$: Sample set of load shedding with respect to $g(Z)$.
- $N$: Number of samples in $Z_g$.
- $i$: Index of samples in sample sets.
- $z^i$: $i$-th sample in $Z_g$.
- $y^i$: $i$-th sample in $Y_g$.
- $n^i$: Number of total stages of $z^i$.
- $\hat{R}_g$: Estimated BR with respect to $g(Z)$.
- $f(Z)$: New joint probability series of $Z$.
- $R_f$: BR with respect to $f(Z)$.
- $\hat{R}_f$: Estimated BR with respect to $f(Z)$.
- $w(z^i)$: Sample weight of $z^i$.
- $m$: Index of the component with new CoFPF.
- $\varphi_m$: New CoFPF of component $m$.
- $n^i_m$: Stage in $z^i$ at which component $m$ fails.
- $K_c$: Set of components whose CoFPFs change.
- $K_u$: Set of components whose CoFPFs do not change.

I. INTRODUCTION

DURING the process of a cascading outage in power systems, the propagation of component failures may cause serious consequences, even catastrophic blackouts [1], [2]. For the sake of effectively mitigating blackout risk, a naive way is to reduce the probability of blackouts, or more precisely, to reduce failure probabilities of system components by means of maintenance or so. Intuitively, it can be readily understood that component failure probabilities (CFPs) have great influence on blackout risk (BR). However, it is not clear how to efficiently quantify such influence, particularly in large-scale power grids.

Generally, CFP largely depends on characteristics of system components as well as working conditions of those components. Since working conditions, e.g., system states, may change during a cascading outage, CFP varies accordingly. Therefore, to quantitatively characterize the influence of CFP on BR, two essential issues need to be addressed. On the one hand, an appropriate probability function of component failure which can...
consider changing working conditions should be well defined first to depict CFP. In this paper, such a function is referred to as component failure probability function (CoFPF). On the other hand, the quantitative relationship between CoFPF and BR should also be explicitly established.

For the first issue, a few CoFPFs have been built in terms of specific scenarios. [3] proposes an end-of-life CoFPF of power transformers taking into account the effect of load conditions. [4] considers the process and mechanism of tree-contact failures of transmission lines, based on which an analytic formulation is proposed. Another CoFPF of transmission lines given in [5] adopts an exponential function to depict the relationship between CFP and some specific indices which can be calculated from monitoring data of transmission lines. This formulation can be extended to other system components in addition to transmission lines, e.g., transformers [6]. Similar works can be found in [7], [8]. In addition, some simpler CoFPFs are deployed in cascading outage simulations [9]–[12]. Specifically, in the famous OPA model [9], CoFPF is usually chosen as a monotonic function of the load ratio, while a piecewise linear function is deployed in the hidden failure model [10]. Such simplified formulations have been widely used in various blackout models [11], [12]. However, it is worthy of noting that these CoFPFs are formulated for specific scenarios. In this paper, we adopt a generic CoFPF to facilitate establishing the relationship between CFP and BR.

The second issue, i.e., the quantitative relationship between CoFPF and BR, is the main focus of this paper. Generally, since various kinds of uncertainties during the cascading process make the number of possible propagation paths explode with the increase of system scale, it is extremely difficult, if not impossible, to calculate the exact value of BR in practice. Therefore, analytically analyzing the relationship between CoFPF and BR is really challenging. In this context, estimated BR by statistics, which is based on a set of samples generated by simulations, appears to be the only practical substitute.

Among the sample-based approaches in BR estimation, Monte Carlo simulation (MCS) is the most popular one to date. However, MCS usually requires a large number of samples with respect to specific CoFPFs for achieving satisfactory accuracy of estimation. Due to the intrinsic inefficiency, MCS is greatly limited in practice, particularly in large-scale systems [13]. More importantly, it cannot explicitly reveal the relationship between CoFPF and BR in an analytic manner. Hence, whenever parameters or forms of CoFPFs change, MCS must be completely re-conducted to generate new samples for correctly estimating BR, which is extremely time consuming. Moreover, due to the inherent strong non-linearity between CoFPF and BR, when multiple CoFPFs change simultaneously, which is a common scenario in practice, BR cannot be directly estimated by using the relationship between BR and individual CoFPFs. In this case, in order to correctly estimate BR and analyze the relationship, the required sample size will dramatically increase compared with the case that a single CoFPF changes. That indicates even efficient variance reduction techniques (which may effectively reduce the sample size in a single scenario [14], [15], but cannot explicitly reveal the relationship as well) are employed, the computational complexity will remain too high to be tractable.

The aforementioned issue gives rise to an interesting question: when one or multiple CoFPFs change, could it be possible to accurately estimate BR without re-conducting the extremely time-consuming blackout simulations? To answer this question, the paper proposes a sample-induced semi-analytic method to quantitatively characterize the relationship between CoFPFs and BR based on a given sample set. Main contributions of this work are threefold.

1) Based on a generic form of CoFPFs, a cascading outage is formulated as a Markov sequence with appropriate transition probabilities. Then an exact relationship between BR and CoFPFs is first rigorously established, which is fundamental for analyses in cascading outages, particularly the correlation analyses.

2) Given a set of blackout simulation samples, an unbiased estimation of BR is derived via exploiting the underlying correlation hidden in cascading simulation data, rendering a semi-analytic expression of the mapping between BR and CoFPFs. It provides a practical tool to efficiently quantitatively analyze the influence of CoFPFs’ change on BR by using simulation data.

3) A high-efficiency algorithm is devised to directly compute BR when CoFPFs change, avoiding re-conducting time-consuming cascading blackout simulations.

The rest of this paper is organized as follows. In Section II, a generic formulation of CoFPF, an abstract model of cascading outages as well as the exact relationship between CoFPF and BR are presented. Then the sample-induced mapping between the unbiased estimation of BR and CoFPFs is explicitly established in Section III. A high-efficiency algorithm is presented in Section IV. In Section V, case studies are given. Finally, Section VI concludes the paper with remarks.

II. RELATIONSHIP BETWEEN COFPFS AND BR

The propagation of a cascading outage is a complicated dynamic process, during which many practical factors are involved, such as hidden failures of components, actions of the dispatch/control center, etc. In this paper, we focus on the influence of random component failures (or more precisely, CFP) on the BR, where a cascading outage can be simplified into a sequence of component failures with corresponding system states, and usually emulated by steady-state models [9], [10], [12]. In this case, individual component failures are only related to the current system state while independent of previous states, which is known as the Markov property. This property enables an abstract model of cascading outages with a generic form of CoFPFs, as we explain below.

A. A Generic Formulation of CoFPFs

To describe a CFP varying along with the propagation of cascading outages, a CoFPF is usually defined in terms of working conditions of the component. In the literature, CoFPF has various forms with regard to specific scenarios [3]–[12]. To generally depict the relationship between BR and CFP with varying
Fig. 1. Cascading process in power systems.

parameters or forms, we first define an abstract CoFPF here. Specifically, the CoFPF of component \( k \), denoted by \( \varphi_k \), is defined as

\[
\varphi_k(s_k, \eta_k) := \Pr(\text{component } k \text{ fails at } s_k \text{ given } \eta_k)
\] (1)

In (1), \( s_k \) represents the current working condition of component \( k \), which can be load ratio, voltage magnitude, etc. \( \eta_k \) is the parameter vector. Both \( \eta_k \) and the form of \( \varphi_k \) represent the characteristics of the component \( k \), e.g., the type and age of component \( k \). It is worthy of noting that the working condition of component \( k \) varies during a cascading outage, resulting in changes of the related CFPs. On the other hand, whereas the cascading process usually does not change \( \eta_k \) and the form of \( \varphi_k \), they can also be influenced due to controlled or uncontrolled factors, such as maintenance and extreme weather, etc. In this sense, (1) provides a generic formulation to depict such properties of CoFPFs.

B. Formulation of Cascading Outages

In this paper, we are only interested in the paths of cascading outages that lead to blackouts as well as the associated load shedding. Then, according to [14], cascading outages can be abstracted as a Markov sequence with appropriate transition probabilities. Specifically, denote \( j \in \mathbb{N} \) as the sequence label and \( X_j \) as the system state at stage \( j \) of a cascading outage. Here, \( X_j \) can represent the power flow of transmission lines, the ON/OFF statuses of components, or other system status of interest. The complete state space, denoted by \( X \), is spanned by all possible system states. \( X_0 \) is the initial state of the system, which is assumed to be deterministic in our study. Under this condition, \( X \) is finite when only the randomness of component failures is considered [14]. Note that \( X_j \) specifies the working conditions of each component at the current stage (stage \( j \)) in the system, consequently determines \( s_k \) in the CoFPF, \( \varphi_k(s_k, \eta_k) \). Then an \( n \)-stage cascading outage can be represented by a series of states, \( X_j \) (see Fig. 1) and mathematically defined as below.

**Definition 1:** An \( n \)-stage cascading outage is a Markov sequence \( Z := \{X_0, X_1, ..., X_j, ..., X_n, X_j \in X, \forall j \in \mathbb{N} \} \) with respect to a given joint probability series \( g(Z) = g(X_0, ..., X_n) \).

In the definition above, \( n \) is the total number of cascading stages, or the length of the cascading outage. Particularly, we denote the set of all possible paths of cascading outages in the power system by \( Z \). Since \( X \) and the total number of components are finite, \( Z \) is finite as well, albeit it may be huge in practice. Then for a specific path, \( z \in Z \), of cascading outages, we have

\[
z = \{x_0, x_1, ..., x_j, ..., x_n \}
\]

\[
g(Z = z) = g(X_0 = x_0, ..., X_j = x_j, ..., X_n = x_n)
\]

where \( g(Z = z) \) is the joint probability of the path, \( z \). For simplicity, we denote \( g(Z = z) \) as \( g(z) = g(x_0, ..., x_1, x_0) \).

Invoking the conditional probability formula and Markov Property, \( g(z) \) can be further rewritten as

\[
g(z) = g(x_n, ..., x_1, x_0)
\]

\[
= g_n(x_n | x_{n-1} ... x_0) \cdot g_{n-1}(x_{n-1} | x_{n-2} ... x_0)
\]

\[
... \cdot g_1(x_1 | x_0) \cdot g_0(x_0)
\]

\[
= g_n(x_n | x_{n-1}) \cdot g_{n-1}(x_{n-1} | x_{n-2}) ... g_0(x_0) \quad (2)
\]

where

\[
g_{j+1}(x_{j+1} | x_j) = \Pr(X_{j+1} = x_{j+1} | X_j = x_j)
\]

\[
g_0(x_0) = \Pr(X_0 = x_0) = 1
\]

It is worthy of noting that this formulation is a mathematical abstraction of the cascading processes in practice and simulation models considering physical details [9], [10], [12]. Different from the high-level statistic models [18], [19], it can provide an analytic way to depict the influence of many physical details, e.g., CFP, on the cascading outages and BR, which will be elaborately explained later on.

The uncertain component failure involved in the propagation process of cascading outages is the main concern of this work. Therefore, we assume the initial system state is deterministic as in [10], [11], [14], and further quantify the influence of CFPs on BR. When a few typical initial system states need to be considered, such as component maintenance, the formulation and the method proposed later on can be separately deployed for analyses in terms of each initial system state.

C. Formulation of Blackout Risk

In the literature, blackout risk has various definitions [14], [20], [21]. Here we adopt the widely-used one, which is defined with respect to load shedding caused by cascading outages.

Due to the intrinsic randomness of cascading outages, the load shedding, denoted by \( Y \), is also a random variable up to the path-dependent propagation of cascading outages. Therefore, \( Y \) can be regarded as a function of cascading outage events, denoted by \( Y := h(Z) \). Then the BR with respect to \( g(Z) \) is defined as the expectation of the load shedding greater than a given level, \( Y_0 \). That is

\[
R_g(Y_0) = \mathbb{E}(Y \cdot \delta_{\{Y \geq Y_0\}})
\] (3)

where, \( R_g(Y_0) \) stands for the BR with respect to \( g(Z) \) and \( Y_0 \); \( \delta_{\{Y \geq Y_0\}} \) is the indicator function of \( \{Y \geq Y_0\} \), given by

\[
\delta_{\{Y \geq Y_0\}} := \begin{cases} 
1 & \text{if } Y \geq Y_0; \\
0 & \text{otherwise.}
\end{cases}
\]
In (3), when the load shedding level is chosen as $Y_0 = 0$, it is simply the traditional definition of BR. If $Y_0 > 0$, it stands for the risk of cascading outages with quite serious consequences, which is closely related to the renowned risk measures, value at risk (VaR) and conditional value at risk (CVaR) [16]. Specifically, the risk defined in (3) is equivalent to CVaR$_{\alpha}$ times $(1 - \alpha)$ with respect to VaR$_{\alpha} = Y_0$ with a confidence level of $\alpha$.

D. Relationship Between BR and CoFPFs

We first derive the probability of cascading outages based on the generic form of CoFPFs. Then we characterize the relationship between BR and CoFPFs.

At stage $j$, the working condition of component $k$ can be represented as a function of the system state $x_j$, denoted by $\phi_k(x_j)$. That is $s_k := \phi_k(x_j)$. Hence the CFP of component $k$ at stage $j$ is $\varphi_k(\phi_k(x_j), \eta_k)$. Without causing confusion, thereafter we abuse the notation $\varphi_k(x_j)$ to stand for $\varphi_k(\phi_k(x_j), \eta_k)$ for simplicity.

Considering stages $j$ and $(j + 1)$, we have

$$g_{j+1}(x_{j+1}|x_j) = \prod_{k \in F(x_j)} \varphi_k(x_j) \cdot \prod_{k \in \bar{F}(x_j)} (1 - \varphi_k(x_j)) \quad (4)$$

In (4), $F(x_j)$ is the component set consisting of the components that are defective at $x_{j+1}$ but work normally at $x_j$, while $\bar{F}(x_j)$ consists of components that work normally at $x_{j+1}$. With (4), (2) can be rewritten as

$$g(z) = \prod_{j=0}^{n-1} g_{j+1}(x_{j+1}|x_j)$$

$$= \prod_{j=0}^{n-1} \left[ \prod_{k \in F(x_j)} \varphi_k(x_j) \cdot \prod_{k \in \bar{F}(x_j)} (1 - \varphi_k(x_j)) \right] \quad (5)$$

Furthermore, substituting $Y = h(Z)$ into (3) yields

$$R_g(y_0) = E(h(Z) \cdot \delta_{\{h(Z) \geq Y_0\}})$$

$$= \sum_{z \in Z} g(z)h(z)\delta_{\{h(z) \geq Y_0\}} \quad (6)$$

Theoretically, the relationship between BR and CoFPFs can be established immediately by substituting (5) into (6). However, this relationship cannot be directly applied in practice, as we explain. Note that, according to (5), the component failures occurring at different stages on a path of cascading outages are correlated with one another. As a consequence, this long-range coupling, unfortunately, produces complicated and nonlinear correlation between BR and CoFPFs. In addition, since the number of components in a power system usually is quite large, the cardinality of $Z$ can be huge. Hence it is practically impossible to accurately calculate BR with respect to the given CoFPFs by directly using (5) and (6). To circumvent this problem, next we turn to using an unbiased estimation of BR as a surrogate, and propose a sample-based semi-analytic method to characterize the relationship.

III. SAMPLE-INDUCED SEMI-ANALYTIC CHARACTERIZATION

A. Unbiased Estimation of BR

To estimate BR, conducting MCS is the easiest and the most extensively-used way. The first step is to generate independent identically distributed (i.i.d.) samples of cascading outages and corresponding load shedding with respect to the joint probability series, $g(Z)$. Unfortunately, $g(Z)$ is indeed unknown in practice. In such a situation, one can heuristically sample the failed components at each stage of possible cascading outage paths in terms of the corresponding system states and CoFPFs. Afterwards, system states at the next stage are determined with the updated system topology. This process repeats until there is no new failure happening anymore. Then a path-dependent sample is generated. This method essentially carries out sampling sequentially using the conditional component probabilities instead of the joint probabilities. (5) provides this method with a mathematical interpretation, which is a application of the Markov property of cascading outages.

Suppose $N$ i.i.d. samples of cascading outage paths are obtained with respect to $g(Z)$. Let $Z := \{z^i, i = 1, \ldots, N\}$ record the set of these samples. Then, the $i$-th cascading outage path contained in the set is expressed by $z^i := \{x_{i0}, \ldots, x_{in}\}$, where $n'$ is the number of total stages of the $i$-th sample. For each $z^i \in Z$, the associated load shedding is given by $y^i = h(z^i)$. All $y^i$ make up the set of load shedding with respect to $g(Z)$, denoted by $Y_g := \{y^i, i = 1, \ldots, N\}$. Then the unbiased estimation of BR is formulated as

$$\hat{R}_g(Y_0) = \frac{1}{N} \sum_{i=1}^{N} y^i \delta_{\{y^i \geq Y_0\}} = \frac{1}{N} \sum_{i=1}^{N} h(z^i)\delta_{\{h(z^i) \geq Y_0\}} \quad (7)$$

Note that (7) applies to $g(Z)$ or the corresponding CoFPFs. That implies the underlying relationship between BR and CoFPFs relies on samples. Hence, whenever parameters or forms of the CoFPFs change, all samples need to be re-generated to estimate the BR, which is extremely time consuming, even practically impossible. Next we derive a semi-analytic method by building a mapping between CoFPFs and the unbiased estimation of BR.

B. Sample-Induced Semi-Analytic Characterization

Suppose the samples are generated with respect to $g(Z)$. Then the sample set is $Z_g$, and the set of load shedding is $Y_g$. When changing $g(Z)$ into $f(Z)$ (both are defined on $Z$), usually all samples of cascading outage paths need to be regenerated. However, inspired by the sample treatment in Importance Sampling [14], it is possible to avoid sample regeneration by revealing the underlying relationship between $g(Z)$ and $f(Z)$. Specifically, for a given path $z^i$, we define

$$w(z^i) := \frac{f(z^i)}{g(z^i)} \quad (z^i \in Z) \quad (8)$$

1 Since the simulation of cascading outages is often independently carried out under the same condition, it is common to assume the samples are i.i.d. [10], [13], [14]. Note that, here a sample represents an entire cascading path.
then each sample in terms of \( f(z) \) can be represented as the sample of \( g(z) \) weighted by \( w(z) \). Consequently, the unbiased estimation of BR in terms of \( f(z) \) can be directly obtained from the sample generated with respect to \( g(Z) \), as we explain.

From (7) and (8), we have

\[
\hat{R}_f(Y_0) = \frac{1}{N} \sum_{i=1}^{N} w(z^i) h(z^i) \delta_{h(z^i) \geq Y_0}
\]

(9)

Obviously, when \( w(z) \equiv 1, z \in \mathbb{Z} \), (9) is equivalent to (7). Moreover, (9) is an unbiased estimation by noting that

\[
\mathbb{E}(\hat{R}_f(Y_0)) = \mathbb{E}\left( \frac{f(Z)}{g(Z)} h(Z) \delta_{h(Z) \geq Y_0} \right) = \sum_{z \in \mathbb{Z}} g(z) \times \frac{f(z)}{g(z)} h(z) \delta_{h(z) \geq Y_0} = R_f(Y_0).
\]

(10)

Equation (10) holds since both \( g(Z) \) and \( f(Z) \) are defined on the same set \( \mathbb{Z} \), which indicates that any possible cascading outages can be sampled with respect to \( g(Z) \) or \( f(Z) \), provided the sample size is large enough.

The unbiasedness of (9) actually guarantees the effectiveness of (9). Moreover, in some special cases where the difference between \( g(Z) \) and \( f(Z) \) is huge, the size of \( \mathbb{Z} \) can be enlarged to reduce the estimation error. Noting that only the information of samples in \( \mathbb{Z} \) is required in (9), the BR with respect to \( f(Z) \), i.e., \( R_f \), can be estimated directly, with no need of regenerating cascading outage samples. That indicates (more) samples only need to be generated with respect to \( g(Z) \) instead of the varying \( f(Z) \). This feature can further lead to an efficient algorithm to analyze BR under varying CoFPFs, which will be discussed in the next section.

### IV. Estimating BR With Varying CoFPFs

#### A. Changing a Single CoFPF

We first consider a simple case, where a single CoFPF changes. Suppose CoFPF of component \( m \) changes from \( \varphi_m \) to \( \tilde{\varphi}_m \), and the corresponding joint probability series changes from \( g(Z) \) to \( f(Z) \). Considering a sample of cascading outage path generated with respect to \( g(Z) \), i.e., \( z^i \in \mathbb{Z} \), we have

\[
f(z^i) = \prod_{j=0}^{n^i-1} f_{j+1}(x^i_{j+1}|x^i_j)
\]

\[
= \prod_{j=0}^{n^i-1} \left[ \prod_{k \in F^m(x^i_j)} \varphi_k(x^i_j) \cdot \prod_{k \in F^m(x^i_j)} (1 - \varphi_k(x^i_j)) \right] \cdot \ldots \Gamma(\tilde{\varphi}_m, z^i)
\]

(11)

where,

\[
\Gamma(\tilde{\varphi}_m, z^i) = \begin{cases} 
\prod_{j=0}^{n^i-1} (1 - \tilde{\varphi}_m(x^i_j)) & : n^i_m = n^i \\
\tilde{\varphi}_m(x^i_j) \prod_{j=0}^{n^i-1} (1 - \varphi_m(x^i_j)) & : \text{otherwise}
\end{cases}
\]

(12)

Here, \( n^i_m \) is the stage in \( z^i \) at which component \( m \) fails. Particularly, \( n^i_m = n^i \) when the \( n \)-th component is still working normally at the last stage of the cascading outage path. Component set \( F^m(x^i_j) := F(x^i_j) \setminus \{m\} \) consists of all the elements in \( F(x^i_j) \) except for \( m \). Similarly \( F^m(x^i_j) := F(x^i_j) \setminus \{m\} \) is the component set including all the elements in \( F(x^i_j) \) except for \( m \). According to (8), the sample weight that only CoFPF of component \( m \) changes is

\[
w(z^i) = \frac{f(z^i)}{g(z^i)} = \frac{\Gamma(\tilde{\varphi}_m, z^i)}{\Gamma(\varphi_m, z^i)}
\]

(13)

Substituting (13) into (9), the unbiased estimation of BR is

\[
\hat{R}_f(Y_0) = \frac{1}{N} \sum_{i=1}^{N} \frac{\Gamma(\tilde{\varphi}_m, z^i)}{\Gamma(\varphi_m, z^i)} h(z^i) \delta_{h(z^i) \geq Y_0}.
\]

(14)

Equation (14) provides an unbiased estimation of BR after changing a CoFPF by only using the original samples.

#### B. Changing Multiple CoFPFs

In this section, we consider the general case that multiple CoFPFs change simultaneously. Invoking the expression of \( f(z^i) \) in (11), we have

\[
g(z^i) = \prod_{k \in K} \Gamma(\varphi_k, z^i)
\]

(15)

\[
f(z^i) = \prod_{k \in K} \Gamma(\tilde{\varphi}_k, z^i) \cdot \prod_{k \in K_u} \Gamma(\varphi_k, z^i)
\]

(16)

where, \( K \) is the universal set of all components in the system; \( K_c \) is the set of components whose CoFPFs change; \( K_u \) is the set of others, i.e., \( K = K_c \cup K_u \); \( \tilde{\varphi}_k \) is the new CoFPF of the \( k \)-th component.

According to (15) and (16), the sample weight is given by

\[
w(z^i) = \prod_{k \in K_c} \frac{\Gamma(\tilde{\varphi}_k, z^i)}{\Gamma(\varphi_k, z^i)}
\]

(17)

Substituting (17) into (9) yields

\[
\hat{R}_f(Y_0) = \frac{1}{N} \sum_{i=1}^{N} \left( \prod_{k \in K_c} \frac{\Gamma(\tilde{\varphi}_k, z^i)}{\Gamma(\varphi_k, z^i)} h(z^i) \delta_{h(z^i) \geq Y_0} \right).
\]

(18)

Equation (18) is a generalization of (14). (18) provides a mapping between the unbiased estimation of BR and CoFPFs. When multiple CoFPFs change, the unbiased estimation of BR can be directly calculated by using (18). Since no additional cascading outage simulations are required, and only algebraic calculations are involved, it is computationally efficient.
C. Algorithm

To clearly illustrate the algorithm, we first rewrite (18) in a matrix form as

$$\hat{R}_f(Y_0) = \frac{1}{N} \mathbf{L} \mathbf{F}_p$$  \hspace{1cm} (19)

In (19), \( \mathbf{L} \) is an \( N \)-dimensional row vector, where \( \mathbf{L}_i = h(z') \delta_{[h(z') \geq Y_0]} / g(z') \). \( \mathbf{F}_p \) is an \( N \)-dimensional column vector, where \( \mathbf{F}_{p,i} = f(z') \).

We further define two \( N \times k_a \) matrices \( \mathbf{A} \) and \( \mathbf{B} \), where \( k_a \) is the total number of all components, \( \mathbf{A}_{ik} = \Gamma(\varphi_k, z') \), \( \mathbf{B}_{ik} = \Gamma(\varphi_k, z') \). According to (16), we have

$$\mathbf{F}_{p,i} = \prod_{k \in K_c} \mathbf{B}_{ik} \cdot \prod_{k \in K_a} \mathbf{A}_{ik}$$  \hspace{1cm} (20)

Then the algorithm is given as follows.

- **Step 1: Generating samples.** Based on the system and blackout model in consideration, generate a set of i.i.d. samples. Record the sample sets \( Z_g \) and \( Y_g \), as well as the row vector \( \mathbf{L} \).
- **Step 2: Calculating \( \mathbf{F}_p \).** Define the new CoFPFs for each component in \( K_c \), and calculate \( \mathbf{B} \) and \( \mathbf{A} \). Then calculate \( \mathbf{F}_p \) according to (20). Particularly, instead of calculation, \( \mathbf{A} \) can be saved in Step 1.
- **Step 3: Data analysis.** According to (19), estimate BR for the changed CoFPFs.

D. An Illustrative Example

To better clarify the algorithm, we employ a toy 4-bus system (see Fig. 2) to illustrate the calculation steps. For simplicity, we number the lines and use symbols to represent CFPs (see Tables I and II).

**Step 1:** First, generate samples with the simulation model.

**Step 2:** Then, we take the \( i \)-th element in \( \mathbf{F}_p \) as an example. Consider the path of the \( i \)-th cascading outage shown in Table II. (At stage 1, line 2 and 3 are tripped. Then at stage 2, line 4 fails and the blackout happens as a consequence. The load shedding is \( y^i \)).

For simplicity, the original CFP of the \( k \)-th line at stage \( j \) is denoted by \( p_{j,k} \), e.g., the original CFP of line 2 at stage 1 is \( p_{1,2} \). Then the probability of the \( i \)-th cascading failure is

$$g(z') = p_{1,2}p_{1,3}(1 - p_{1,1})(1 - p_{1,4})(1 - p_{1,5})$$

$$\ldots \times p_{2,4}(1 - p_{2,1})(1 - p_{2,5})$$

And we have

$$\mathbf{L}_i = \frac{y^i \delta_{\{y^i \geq Y_0\}}}{g(z')}$$

$$\mathbf{A}_{i,k} = (1 - p_{1,4})p_{2,4}$$

Other elements in the \( i \)-th row of \( \mathbf{A} \) can be obtained similarly.

On the other hand, suppose the CFP of line 4 at stage 1 and stage 2 change to \( p_{1,4}' \) and \( p_{2,4}' \), respectively. Then \( \mathbf{B}_{i4} = (1 - p_{1,4}')p_{2,4}' \). Other elements in the \( i \)-th row of \( \mathbf{B} \) can be obtained similarly.

If we only consider the CFP of line 4 changes, then \( \mathbf{F}_{pi} = p_{1,2}p_{1,3}(1 - p_{1,1})(1 - p_{1,4}')(1 - p_{1,5}) \times p_{2,4}'(1 - p_{2,1})(1 - p_{2,5}) \). Other scenarios are similar.

**Step 3:** Based on the previous calculation, the BR can be directly estimated using (19).

E. Some Implications

The proposed method has important implications in blackout-related analyses. Two of typical examples are: efficient estimation of BR considering extreme weather conditions and the risk-based maintenance scheduling.

For the first case, as well known, extreme weather conditions (e.g., typhoon) often occur for a short time but affect a wide range of components. The failure probabilities of related components may increase remarkably. In this case, the proposed method allows an efficient identification of the most effective candidate devices in the system for mitigating BR. Specifically, suppose that one only considers simultaneous maintenance of at most \( d_{m} \) components. Then the number of possible scenarios is up to \( \sum_{d=1}^{d_{m}} C(k_a, d) \), which turns to be intractable in a large practical system (\( C(k_a, d) \) is the number of \( d \)-combinations from \( k_a \) elements). Moreover, in each scenario, a great number of cascading outage simulations are required to estimate BR, which is extremely time consuming, or even practically impossible. In contrast, with the proposed method,
one only needs to generate the sample set in the base scenario. Then BRs for other scenarios can be directly calculated using only algebraic calculations, which is very simple and computationally efficient.

V. CASE STUDIES

A. Settings

In this section, the numerical experiments are carried out on two systems. One is the IEEE 300-bus system and the other is a real provincial power system in China. Moreover, we employ the widely-used OPA model to generate the samples in $Z_g$. Particularly, since the proposed method aims to quantify the influence of CFP on BR with respect to a deterministic initial state, the slow dynamic representing the load growth is omitted [14], [17], [22]. Then, the basic sampling steps which simulate the propagation of cascading outages are summarized as follows.

- **Step 1: Data initialization.** Initialize the system data and parameters. Particularly, define specific CoFPFs for each component. The initial state is $x_0$.
- **Step 2: Sampling outages.** At stage $j$ of the $i$-th sampling, according to the system state, $x_j^i$, and CoFPFs, simulate the component failures with respect to the failure probabilities.
- **Step 3: Termination judgment.** If new failures happen in Step 2, recalculate the system state $x_j^i$ at stage $j + 1$ with the new topology, and go back to Step 2; otherwise, one sampling ends. The corresponding samples are $z^i = \{x_0, x_1^i \ldots x_j^i\}$ and $y^i$. If all $N$ simulations are completed, the sampling process ends.

In this simulation model, the state variables $X_j$ are chosen as the ON/OFF statuses of all components and power flow on corresponding components at stage $j$. Meanwhile, the random failures of transmission lines and power transformers are considered. The CoFPF we use is

$$\varphi_k(s_k, \eta_k) = \begin{cases} p_{\min}^{k} & s_k < s^k_d \\ p_{\min}^{k} - p_{\min}^{k}(s_k - s^k_d) + p_{\max}^{k} & \text{else} \\ p_{\max}^{k} & s_k > s^k_u \end{cases}$$

(21)

where $s^k$ is the load ratio of component $k$ and $\eta_k = [p_{\min}^{k}, p_{\max}^{k}, s^k_d, s^k_u]$ [10]. Specifically, $p_{\min}^{k}$ denotes the minimum failure probability of component $k$ when the load ratio is less than $s^k_d$; $p_{\max}^{k}$ denotes the maximum failure probability when the load ratio is larger than $s^k_u$. Usually it holds $0 < p_{\min}^{k} < p_{\max}^{k} < 1$, which depicts certain probability of hidden failures in protection devices.

It is worthy of noting that the simulation process with specific settings mentioned above is a simple way to emulate the propagation of cascading outages. We only use it to demonstrate the proposed method. The proposed method can apply when more realistic models and parameters are adopted.

B. Case 1: IEEE 300-Bus System

1) Unbiasedness of the Estimation of BR: In this case, we will show that our method can achieve unbiased estimation of BR. We first choose the initial parameters as $s^k_d = 0.97$, $s^k_u = 1.3$, $p_{\max}^{k} = 0.9995$, $p_{\min}^{k} \sim U[0.002, 0.006]$, $k \in K$, and carry out 100,000 cascading outage simulations with the initial parameters. Then the sample set $Z_g$ and related $L$ are obtained. Afterward we randomly choose a set of failure components, $K_r$, including two components. Accordingly, we modify the parameters, $\eta_k$, of their CoFPFs to $p_{\min}^{k} = p_{\min}^{k} - 0.001, k \in K_r$. In terms of the new settings and various load shedding levels, we estimate the BRs by using (19). For comparison, we re-generate 100,000 samples under the new settings and estimate the BRs by using (7). The results are given in Fig. 3.

Fig. 3 shows that the estimations of BR with two methods are almost the same, which indicates the proposed method can achieve unbiased estimation of BR. Note that our method requires no more simulations, which is much more efficient than traditional MCS, and scalable for large-scale systems.

2) Parameter Changes in CoFPFs: In this case, we test the performance of our method when parameters, $\eta_k$, of some CoFPFs change. The sample set $Z_g$ and related $L$ are based on the 100,000 samples with respect to the initial parameters. We consider two different settings: 1) $Y_0 = 0$; 2) $Y_0 = 1500$. Statistically, we obtain $\hat{R}_g(0) = 54.2$ and $\hat{R}_g(1500) = 0.43$, respectively.

Since there are 411 components in the system, we consider $k_0 = 411$ different scenarios. Specifically, we change each CoFPF individually by letting $p_{\min}^{k} = p_{\min}^{k} - 0.001$. Using the proposed method, BRs can be estimated quickly. Some results are presented in Table III ($Y_0 = 0$) and Table IV ($Y_0 = 1500$). Particularly, the average computational times of unbiased estimation of BR in each scenario in Tables III and IV are 0.004 s and 0.00001 s, respectively.

Table III shows the top ten scenarios having the lowest value of BR as well as the average risk of all scenarios. Whereas reducing failure probabilities of certain components can effectively mitigate BR, others have little impact. For example, decreasing $p_{\min}^{k}$ of component #204 results in 6.0% reduction of BR, while the average ratio of risk reduction is only 0.2%. This result implies that there may exist some critical components which play a core role in the propagation of cascading outages and promoting load shedding. Our method enables a scalable way
to efficiently identify those components, which may facilitate effective mitigation of BR.

When considering \( \gamma_0 = 1500 \), which is associated with serious blackout events, it is interesting to see the most influential components in Table IV are different from that in Table III. In other words, the impact of CoFPF varies with different load shedding levels, which demonstrates the complex relationship between BR and CoFPFs. To better show this point, we choose four typical components (#312, #372, #307 and #259) and calculate the risk reduction ratios with respect to two CoFPFs simultaneously. Our method indeed provides a computationally efficient tool to conveniently analyze such relationships in practice.

Then we decrease \( p_{\text{min}}^k \) of two CoFPFs simultaneously. \( Z_y, L \) are the same as before, and the number of scenarios is \( C(k_u, 2) = C(411, 2) \). The calculated unbiased estimations with respect to two \( \gamma_0 \) are shown in Table V. It is no surprise that the risk reduction ratios are more remarkable compared with the results in Tables III and IV, where only one CoFPF decrease. However, it should be noted that the pairs of components in Table V are not simple combinations of the ones shown in Tables III and IV, where only one CoFPF decrease. The reason is that the relationship between BR and CFP is complicated and nonlinear, which actually results in the difficulties in analyses as we demonstrate in Section V.

3) Form Changes in CoFPFs: In this case, we show the performance of the proposed method when the form of CoFPFs changes. The new form of CoFPF of component \( k \) is

\[
\varphi_k(s_k, \eta_k) = \left\{ \begin{array}{ll}
\max(\varphi_k, a e^{bs_k}) : & s_k < s^k_u \\
p_{\text{max}}^k : & s_k \geq s^k_u
\end{array} \right.
\]

(22)

where \( a = p_{\text{min}}^k \) and \( b = \ln(p_{\text{max}}^k/p_{\text{min}}^k) \) are corresponding parameters. \( \varphi_k, p_{\text{min}}^k, p_{\text{max}}^k, s^k_u, s^k_d \) are the same as the ones in (21). Obviously, the failure probabilities of individual components are amplified in this case.

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**TABLE III**

| Component index | \( p_{\text{min}}^k \) \( \times 10^{-3} \) | Blackout risk | Risk reduction ratio(%) |
|-----------------|---------------------------------|-----------------|-------------------------|
| 204             | 5.8                             | 50.97           | 6.0                     |
| 312             | 5.1                             | 51.93           | 4.2                     |
| 372             | 3.0                             | 53.43           | 1.5                     |
| 114             | 4.1                             | 53.46           | 1.4                     |
| 307             | 3.7                             | 53.53           | 1.3                     |
| 410             | 3.6                             | 53.68           | 1.0                     |
| 117             | 4.0                             | 53.69           | 1.0                     |
| 63              | 2.3                             | 53.70           | 1.0                     |
| 259             | 3.0                             | 53.90           | 0.6                     |
| 126             | 2.7                             | 53.92           | 0.5                     |

...  

Mean value 4.0 54.13 0.2

---

**TABLE IV**

| Component index | \( p_{\text{min}}^k \) \( \times 10^{-3} \) | Blackout risk | Risk reduction ratio(%) |
|-----------------|---------------------------------|-----------------|-------------------------|
| 259             | 3.0                             | 0.358           | 16.7                    |
| 254             | 4.3                             | 0.380           | 11.4                    |
| 204             | 5.8                             | 0.382           | 11.0                    |
| 312             | 5.1                             | 0.403           | 6.0                     |
| 93              | 3.0                             | 0.403           | 6.0                     |
| 325             | 2.2                             | 0.404           | 5.9                     |
| 48              | 3.0                             | 0.404           | 5.9                     |
| 378             | 2.6                             | 0.405           | 5.7                     |
| 116             | 2.2                             | 0.406           | 5.5                     |
| 305             | 2.2                             | 0.407           | 5.3                     |
| ...             | ...                             | ...             | ...                     |

Mean value 4.0 0.427 0.5

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**TABLE V**

| Component index | Risk reduction ratio \( (\gamma_0 = 0) \) | Component index | Risk reduction ratio \( (\gamma_0 = 1500) \) |
|-----------------|---------------------------------|-----------------|-------------------------|
| (204,312)       | 10.2                            | (204,259)       | 25.5                    |
| (204,327)       | 7.5                             | (254,259)       | 24.5                    |
| (114,204)       | 7.4                             | (93,259)        | 22.6                    |
| (204,307)       | 7.3                             | (259,312)       | 22.2                    |
| (63,204)        | 7.0                             | (259,378)       | 21.8                    |
| (204,410)       | 7.0                             | (259,305)       | 21.8                    |
| (117,204)       | 7.0                             | (259,325)       | 21.6                    |
| (204,259)       | 6.6                             | (116,259)       | 21.3                    |
| (126,204)       | 6.6                             | (40,259)        | 21.1                    |
| (204,301)       | 6.5                             | (48,259)        | 21.1                    |
| ...             | ...                             | ...             | ...                     |

Mean value 0.3  Mean value 1.0

---
Similar to the previous cases, we use the proposed method to calculate the unbiased estimations of BRs when some CoFPFs change from (21) to (22). The comparison results of our method and MCS are presented in Fig. 5. In addition, BR in several typical scenarios is shown in Tables VI and VII. These results empirically confirm the efficacy of our method.

4) Computational Efficiency: We carry out all tests on a computer with an Intel Xeon E5-2670 of 2.6 GHz and 64 GB memory. It takes 107 minutes to generate $Z_g(100,000$ samples) with respect to the initial parameters. Then we enumerate all $\sum_{d=1}^{2} C(k_d,d) = 84666$ scenarios. In each scenario, the parameters and forms of one or two CoFPFs are changed. Then we calculate the unbiased estimations of BR with $Y_0 = 0$ and $Y_0 = 1500$ by using the proposed method. The complete computational times are given in Tables VIII and IX. It is worthy of noting that the computational times of risk estimation in tables are the total times for enumerating all the 84666 scenarios. It takes only about 10 minutes to calculate $B$, and additional 10 minutes to computing BRs. On the contrary, it will take about $10^7 \times 84666 \approx 9,000,000$ minutes for the MCS method, which is practically intractable.

C. Case 2: The Real 1122-Bus System

In this case, we show the proposed method has great performance in a large real power system as well. We adopt the real data of a provincial power system in China, which includes 1,122 buses, 1,792 transmission lines and transformers. Specifically, we choose $p_{\text{min}}^{k} \sim U[0.0005, 0.001]$, while other simulation conditions are the same as the previous cases. Moreover, $Z_g$ includes 100,000 samples, and $p_{\text{min}}^{k}$ are reduced by 0.0002 to represent the changes of CoFPF in analyses.

First, we randomly change the CoFPFs of 6 components. The estimated BRs with respect to different load shedding levels with two methods (directly sampling and estimation via the proposed method) are shown in Fig. 6, which verify the unbiasedness of the proposed method in such a large system.

Then CoFPFs of one or two components are changed. All the $C(1792, 1) + C(1792, 2) = 1,606,528$ scenarios are enumerated, and the results in typical scenarios are given in Table X.
It can be found that there are a few critical components in this real system, which have much larger influence on BR.

Finally, we demonstrate the computational efficiency. In this case, it takes us 8,400 minutes to generate $Z_n$, while it takes us 51.2 minutes to calculate $B$. When estimating BR, we enumerate $C(1792, 1) + C(1792, 2) = 1, 606, 528$ scenarios and the computing time is only 53 minutes. On the contrary, directly re-generating samples turns out to be too time-consuming to be acceptable. Indeed the computing time for enumeration can be roughly estimated as 8,400 minutes $\times 1, 606, 528 \approx 1.35e^{10}$ minutes $\approx 25675$ years.

Another interesting observation from the test results is that, when using the proposed method, generating samples takes most of the computing time. In contrast, estimating BR with respect to a few CoFPFs of interest is extremely efficient. In this context, if enough samples in $Z_n$ can be generated in advance, the proposed method has great potential to be employed to online estimate BR when CoFPFs change.

VI. CONCLUSION WITH REMARKS

In this paper, we propose a sample-induced semi-analytic method to efficiently quantify the influence of CFP on BR. Theoretical analyses and numerical experiments show that:

1) With appropriate formulations of cascading outages and a generic form of CoFPFs, the relationship between CoPF and BR is exactly characterized and can be effectively estimated based on samples.

2) Taking advantages of the semi-analytic expression between CoFPFs and the unbiased estimation of BR, the BR can be efficiently estimated when CoFPFs change, and the relationship between the CFP and BR can be analyzed correspondingly.

Numerical experiments reveal that the long-range correlation among component failures during cascading outages is really complicated, which is often considered closely related to self-organized criticality and power low distribution. Our works not only can efficiently estimate BR when CoFPs change, but also serve as a step towards providing a scalable and efficient tool for further understanding the failure correlation and the mechanism of cascading outages. Our ongoing work includes the application of the proposed method in making maintenance plans and risk evaluation considering extreme weather conditions, etc.

| Component index | Risk reduction ratio | Component index | Risk reduction ratio |
|-----------------|----------------------|-----------------|----------------------|
| 1694            | 3.2                  | (1430,1694)     | 5.8                  |
| 1430            | 2.5                  | (1431,1431)     | 5.4                  |
| 1431            | 2.0                  | (1430,1431)     | 4.6                  |
| 1551            | 1.2                  | (1551,1694)     | 4.4                  |
| 1552            | 1.1                  | (1552,1694)     | 4.3                  |
| ...             | ...                  | ...             | ...                  |
| Mean value      | 0.05                 | Mean value      | 0.09                 |

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