A Fast Contingency Screening Technique for Generation System Reliability Evaluation

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Abstract—In most existing reliability evaluation techniques, the stopping rules applied for contingency enumeration are either a given number of states with the highest probabilities or the states up to a specified failure order. A fast contingency screening technique (FCST) for generation system reliability evaluation is proposed in this paper. In this technique, contingency states are searched and ranked based on the severity coefficients determined by both state probabilities and outage capacities of the failed units. Several severity coefficients for a unit are defined and examined based on reliability and capacity factors. The replaceable neighboring states of a state and the minimum set of the neighboring states are defined to further reduce computation time. The merits of the proposed techniques and severity coefficients are validated by evaluating the East-China Power Grid.

Index Terms—generation system reliability; state selection; contingency screening; available generation capacity

I. INTRODUCTION

With high penetration of renewable sources, power systems will operate more often under uncertain load and generation conditions. Therefore system reliability under various conditions should be determined. An important factor which limits the computation speed of reliability evaluation of large power systems is the enormous number of contingency states. Therefore it is essential to develop fast and accurate state selection techniques for reliability evaluation.

In order to obtain the most accurate reliability results in a limited time, only those states with the most significant contribution to system reliability should be investigated. Most existing reliability techniques select credible states up to a given order of outage states or the states with the total probability which is larger than a given value [1-4]. The high order outage states with large probabilities may be ignored if only a given order of outage states is considered in evaluation. This may lead to the accuracy of reliability results. Several techniques have been developed to consider the effect of high level outage states without significantly increasing evaluation time. The authors [5-7] presented a state extension algorithm to collectively include the effects of some uninvestigated high order outage states based on system coherence. The techniques can be used to estimate basic failure probability, frequency and duration indices. However, the algorithm cannot include all the high order contingencies with large reliability impact. In order to solve the problem, a fast sorting algorithm (FSA) was proposed [8]. However, the number of computations and comparisons in the FSA becomes enormous for large power systems.

On the other hand, the impact of an outage state on system reliability depends not only on the failure probability of the failed units but also their available generation capacity. Failure of a unit with large generation capacity may cause more load curtailment than that for the loss of a small size unit. Therefore a contingency state with small probability may have large load curtailment if the total outage capacity of the failed units is large. However, this issue has not been considered in the existing state selection techniques.

This paper proposes a fast contingency screening technique (FCST) to select the required number of most severe contingency states based on both generator reliability and capacity. Reliability and capacity factors are defined for a generating unit to represent the combined impact on system reliability. Several severity coefficients for a unit are defined to represent the combined effect and to find more suitable coefficients which can provide more accurate reliability results. Contingency states are searched and ranked based on...
severity coefficient instead of only outage probability in the existing techniques. The replaceable neighboring states are defined and the minimum set of the neighboring states are searched in the FCST to further reduce the number of computations and comparisons in state selection process.

Section II presents the proposed fast contingency screening technique and the associated definitions and propositions. The state sorting procedure is also introduced in this section. A test system is evaluated using the proposed technique in Section III. The advantages of the proposed technique are illustrated by comparing the results with those from the existing technique. Section IV is the conclusion.

II. FAST CONTINGENCY SCREENING TECHNIQUE

Reliability and available generation capacity of a unit are two important factors to contribute to system reliability. In this section, a probability ratio and two capacity coefficients for a unit are defined to separately represent the reliability and capacity impacts on system reliability. The combination effect of the two factors on system reliability is investigated by using the five severity coefficients. Generating units in a power system are arranged in ascending order based on the proposed severity coefficients to increase the speed of state selection. The most severe system outage states are searched from different outage levels. The severity coefficient of a state is determined based on the severity coefficients of the failed units. The concepts of a neighboring state and a replaceable neighboring state are introduced to increase the speed of searching process. A fast contingency screening technique is presented to search the required number of the outage states and the minimum set of the neighboring states are introduced to increase the speed of searching process. A fast contingency screening technique is presented to search the required number of the outage states.

Definitions

The reliability of unit \( j \) is represented by availability \( p_{uj} \).

In order to simplify the searching process, a reliability factor is defined based on \( p_{uj} \) and \( p_{dj} \).

**Definition 1:** The reliability factor of unit \( j \) is represented by a probability ratio \( \theta_j \) as:

\[
\theta_j = \frac{1 - p_{dj}}{p_{uj}} \quad (1)
\]

In order to consider the impact of generator capacity on system reliability, two capacity factors are considered for a generator. The contribution of unit capacity to system reliability can be represented by the ratio of unit capacity to the total system generation capacity or the ratio of unit capacity to the capacity of the largest unit.

**Definition 2:** The capacity factor of unit \( j \) is represented by a capacity coefficient \( \omega_j \).

The first capacity coefficient \( \omega_j \) of unit \( j \) is defined as the percentage contribution of unit capacity to the total system generation capacity.

\[
\omega_j = \frac{P_j}{\sum_{i=1}^{n} P_i} \quad (2)
\]

where \( n \) is the number of the committed units, \( P_j \) is the available generation capacity of unit \( j \).

The second capacity coefficient \( \omega_j^2 \) of unit \( j \) is defined as the ratio of unit capacity to the largest committed unit.

\[
\omega_j^2 = \frac{P_j}{P_{max}} \quad (3)
\]

where \( P_{max} \) is the available generation capacity of the largest committed unit.

To determine the percentage contribution to the system reliability from unit reliability and capacity factors of a unit is a new issue. It may depend on the failure rate and capacity of each unit, total system generation capacity, and the combination of different types of units in the system. Therefore the different contribution weights of the two factors have to be investigated to determine a suitable severity coefficient which can provide the more accurate reliability results.

**Definition 3:** The contribution of unit \( j \) to system reliability is represented by severity coefficient \( \phi_j \) with considering the combination effect of the two factors. Five severity coefficients are defined in this paper.

\[
\phi_j^1 = \theta_j \quad (4)
\]

\[
\phi_j^2 = \theta_j \omega_j \quad (5)
\]

\[
\phi_j^3 = \theta_j \omega_j^2 \quad (6)
\]

\[
\phi_j^4(a) = \theta_j + a \omega_j \quad (7)
\]

\[
\phi_j^5(a) = \theta_j + a \omega_j^2 \quad (8)
\]

where \( a \) is the weighting factor of the capacity coefficient which have to be selected for different unit combination of power systems and reliability indices.

**Definition 4:** The sequence number \( j \) of a unit in a power system is determined by the severity coefficient. All units in a power system are arranged as \( (1, 2, 3, \ldots, n) \) in the descending order of the severity coefficients as:

\[
\phi_1 \geq \phi_2 \geq \ldots \geq \phi_j \geq \ldots \geq \phi_n \quad (9)
\]

**Definition 5:** A level-\( i \) outage state \( S_{im} \) is a system state with \( i \) failed units which are arranged as \( S_{im}(2, 3, 5, \ldots) \) in the ascending order of sequence numbers. The severity coefficient and probability of the \( m^{th} \) level-\( i \) state \( S_{im} \) are presented by \( SC_{S_{im}} \) and \( P_{S_{im}} \) respectively. For example, the \( m^{th} \) level-3 state with the failed units 4, 5 and 7 is represented by \( S_{3m}(4,5,7) \). The \( SC_{S_{im}} \) and \( P_{S_{im}} \) can be calculated using the following equations.
\[
SC_{s_{im}} = \varphi_x \cdot \varphi_y \cdot \varphi_z
\]
\[
p_{s_{im}} = (\theta_x \cdot \theta_y \cdot \theta_z) \prod_{j=1}^{n} p_{uj}
\]

**Minimum Set of Neighboring States**

**Definition 6:** The neighboring states of a state are defined in [8]. The two level-1 outage states are the neighboring states if only one failed component in the two states is different. The set of the neighboring states of level-1 state \( S_{im} \) includes all its neighboring states and is represented by \( D_{s_{im}} \). For example, the set of the neighboring states of a level-3 state \( S_3(1,2,4) \) is \( D_{s_{im}} = \{S_1(1,2,5), S_1(1,3,4), S_1(2,3,4)\} \).

**Definition 7:** Assume that \( S_{im+1} \) and \( S_{im+2} \) are the two neighboring states of \( S_{im} \). If the sequence numbers of the failed units in \( S_{im+1} \) are sequentially smaller than or equal to those in \( S_{im+2} \), \( S_{im+1} \) is a replaceable neighboring state of \( S_{im+2} \). For example, \( S_1(1,3,4) \) in the set of the neighboring states \( D_{s_{im}} = \{S_3(1,2,5), S_1(1,3,4), S_1(2,3,4)\} \) is a replaceable state of \( S_1(2,3,4) \). However, \( S_1(1,2,5) \) is not the replaceable state of \( S_1(2,3,4) \).

**Proposition 1:** If the sequence numbers of the failed units in \( S_{im} \) are sequentially smaller than or equal to those in \( S_{il} \), or \( S_{il} \) is the neighboring state of \( S_{im} \), the severity coefficient of \( S_{im} \) is larger than or equal to that of \( S_{il} \), i.e., \( SC_{s_{im}} \geq SC_{s_{il}} \).

**Proposition 2:** If the replaceable state \( S_{im+1} \) of \( S_{im+2} \) exists in the current set \( D_{s_{im}} \) of the neighboring states, \( S_{im+2} \) will exist in the future set of the neighboring states. Therefore, \( S_{im+2} \) in \( D_{s_{im}} \) can be ignored to reduce the number of computations and comparisons during the searching process. A minimum set is formed by ignoring all the replaceable states in \( D_{s_{im}} \).

**Proposition 3:** The minimum set \( \hat{D}_{s_{im}} \) of the neighboring states of \( S_{im} \) is a set of states with the largest severity coefficients.

\[
\hat{D}_{s_{im}} = \{S_{im+1}, S_{im+2}, \ldots, S_{im+k}\} \quad k \leq i
\]

where \( S_{im+j} \) satisfies the following condition.

Assuming that the sequence number of the \( x^{th} \) failed unit is \( \alpha \) and the number of the \( (x+1)^{th} \) failed unit is \( \beta \) in \( S_{im} \). If there is a failed unit with the number \( b = a+1 < c \), a neighboring state of \( S_{im} \) can be obtained by replacing unit \( \alpha \) by \( \beta \). A neighboring state in \( \hat{D}_{s_{im}} \) can be obtained by replacing a failed unit in \( S_{im} \). The number of level-\( i \) neighboring states in the minimum set is smaller than or equal to \( i \).

**Definition 8:** The set of the minimum sets for the first \( m \) level-\( i \) outage states \( \{(S_{i1}, S_{i2}, \ldots, S_{im})\} \) is represented by \( \hat{D}_{s_{im}} \) and determined as:

\[
\hat{D}_{s_{im}} = \left\{ \hat{D}_{s_{im+1}} \cup \hat{D}_{s_{im}} \right\}
\]

\[
\mathbf{m} = 1, L \leq \mathbf{m} < \mathbf{n}_i S_{in}\]

**D. Sorting the states for all levels**

The proposed algorithm can be applied to determine the required number of the most severe states in the descending severity order without enumerating and comparing all system states. The flowchart of the procedure is shown in Fig. 1, where \( n_i \) is the number of the required number of system states to be considered for reliability evaluation, \( N \) is the number of system states having been selected during the state selection process, and \( k \) is the maximum outage level in \( \hat{D}_{km} \).

The procedure includes the following major steps:

**Step1:** The simulation starts from the normal state \( S_0 \) in which no unit is failed. Set \( N=0, k=0, i=1 \) and \( \hat{D}_{s_{im}} = \{S_0\} \).

**Step2:** Calculate the severity coefficient of each state in \( \hat{D}_{s_{im}} \), and arrange the states in the descending order of severity coefficients.

**Step3:** Select the first state \( S_{im} \) in \( \hat{D}_{s_{im}} \) and update system reliability indices. If \( N > n_i \), stop the procedure. Otherwise go to Step 4.

**Step4:** Set \( i \) as the outage level of the selected state \( S_{im} \). If \( i > k \), go to step 5; Otherwise go to Step 6.

**Step5:** Set \( k = k+1 \) and add \( S_{im} \) into \( \hat{D}_{s_{im}} \).
Step 6: Determine the minimum set of neighboring states $\tilde{D}_{sm}$ for $S_m$ and $\tilde{D}_{mn}$ and add $\tilde{D}_{om}$ into $\tilde{D}_{on}$.

Step 7: Set $N=N+1$, go to Step 2.

III. RELIABILITY EVALUATION

A. Reliability Indices

The proposed FCST can be used to calculate the reliability indices proposed in the publications. The Expected Demand Not Supplied (EDNS) and Loss of Load Probability (LOLP) are evaluated in this paper to illustrate the proposed FCST.

The LOLP is calculated by

$$\text{LOLP} = \sum_{s \in O} p_s$$  (14)

The EDNS is calculated by

$$\text{EDNS} = \sum_{s \in O} p_s (P_{Os} - P_{Gs})$$  (15)

where $p_s$ and $P_{Gs}$ are the probability and available generation capacity of state $s$ respectively, $P_{Os}$ is the load level during state $s$, and $O$ is the set of the outage states for which $P_{Gs} < P_{Os}$. The reliability indices can be calculated for the selected states during state selection process. The stop rule of simulation can be either a given number of contingency states or a given accuracy for a specified reliability index.

B. Test System

The FCST is illustrated by the East-China Power Grid. There are 281 committed units in the system. The available generation capacity and load are 116264 MW and 109241 MW respectively. The parameters of the committed units are shown in Table I. All the simulations in the paper are performed in an Intel-T2300 1.66 GHz computer with 1 Gigabyte memory.

<table>
<thead>
<tr>
<th>Available generation capacity</th>
<th>Unit numbers</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>100MW</td>
<td>18</td>
<td>0.997433</td>
</tr>
<tr>
<td>150MW</td>
<td>48</td>
<td>0.997759</td>
</tr>
<tr>
<td>300MW</td>
<td>33</td>
<td>0.998395</td>
</tr>
<tr>
<td>600MW</td>
<td>104</td>
<td>0.998643</td>
</tr>
<tr>
<td>1000MW</td>
<td>78</td>
<td>0.998679</td>
</tr>
</tbody>
</table>

C. Accuracy and Efficiency Analysis of the FCST

In order to illustrate the improvement of the proposed replaceable neighboring states and the minimum set of neighboring states of the FCST on computing time and reliability indices, the same severity coefficient $\phi_j$ is used for both the proposed FCST and the existing FSA techniques. The EDNS, the number of the compared states $n_c$ and the CPU time during the search process for different $n_1$ by using the two techniques are shown in Table II.

It can be seen from the table that the number of the compared states $n_c$ during the searching process of the FCST is much less than the FSA for the same $n_1$. For the same $n_1=10^4$, $n_c$ is about $3.5 \times 10^6$ for the FSA and $n_c$ is less than $0.3 \times 10^6$ for the FCST. For $n_1=20 \times 10^3$, the computing time for the FSA is over 1000 seconds and only 176 seconds for the FCST. Therefore the FCST is much faster than the FSA. On the other hand, the EDNS obtained by using the FCST is larger than that from the FSA for the same $n_1$. This means that the more severe outage states have been selected by using the FCST compared to the FSA. The FCST provides the more accurate reliability results for the same $n_1$.

Fig. 2 shows the average number of the compared states for different $n_1$ in term of the ratio $n_c/n_1$ with the FSA and FCST. The figure shows that the average number of the compared states for the FSA increases significantly when $n_1$ increases. The $n_c$ for the FSA is about 400 times of $n_1=10^1$, and 1382 times of $n_1$ when $n_1=10^3$. However, the $n_c$ for the FCST is only about 100 times of $n_1$ for different $n_1$. This means that $n_c$ increases linearly with $n_1$. It can be concluded that the FCST is the more robust method in term of the efficiency of state selection.

D. Effect of Severity Coefficients

The impacts of the proposed severity coefficients on the accuracy of reliability indices are studied in this section. The basic parameters of the East-China Power Grid provided in Section B are used. In this case the reliability results from the five severity coefficients are shown for the same $n_1=25 \times 10^3$.

Table III shows the maximum EDNSs calculated by using $\phi_{j}^1(a)$, $\phi_{j}^1(a)$ and $\phi_{j}^1(a)$ for $n_1=25 \times 10^3$. The $\phi_j^1$ is the coefficient without considering capacity factor.

![Graph showing the n_c/n_1 ratio for different n_1 using the two methods.](image)

**TABLE III**

<table>
<thead>
<tr>
<th>n_1 x 10^3</th>
<th>Methods</th>
<th>CPU time</th>
<th>n_c</th>
<th>EDNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>FSA</td>
<td>3s</td>
<td>3,502,266</td>
<td>49.57</td>
</tr>
<tr>
<td></td>
<td>FCST</td>
<td>&lt;3s</td>
<td>266,638</td>
<td>50.24</td>
</tr>
<tr>
<td>50</td>
<td>FSA</td>
<td>14s</td>
<td>18,742,624</td>
<td>51.84</td>
</tr>
<tr>
<td></td>
<td>FCST</td>
<td>12s</td>
<td>5,615,175</td>
<td>53.08</td>
</tr>
<tr>
<td>100</td>
<td>FSA</td>
<td>90s</td>
<td>138,261,143</td>
<td>54.14</td>
</tr>
<tr>
<td></td>
<td>FCST</td>
<td>56s</td>
<td>7,549,774</td>
<td>54.15</td>
</tr>
<tr>
<td>200</td>
<td>FSA</td>
<td>&gt;1000s</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>FCST</td>
<td>176s</td>
<td>20,998,884</td>
<td>54.29</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
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</tr>
</tbody>
</table>

**TABLE II**

**THE RESULTS FOR DIFFERENT n_1**

**THE MAXIMUM EDNSs FOR DIFFERENT SEVERITY COEFFICIENTS**
It can be concluded from the above analysis that the introduction of the capacity coefficient can improve the accuracy of reliability evaluation. However, a suitable value of \( a \) has to be selected to obtain more accurate reliability indices for \( \varphi_j^1(a) \) and \( \varphi_j^2(a) \).

<table>
<thead>
<tr>
<th>( a )</th>
<th>( \varphi_j^1 )</th>
<th>( \varphi_j^2 )</th>
<th>( \varphi_j^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>51.57</td>
<td>51.89</td>
<td>51.70</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The \( EDNS \)s for the five severity coefficients are evaluated with the FCST under a given \( n_1=25\times10^3 \). The \( EDNS \)s for \( \varphi_j^1(a) \) and \( \varphi_j^2(a) \) are the maximum values under the optimal factor \( a \). The results are shown in Fig. 3. It can be seen from Fig. 9 that \( \varphi_j^1(a) \) provides the most accurate reliability result.

### IV. CONCLUSION

A fast contingency screening technique for generating system reliability evaluation is proposed in this paper. In this technique, the sequence of units is decided by the severity coefficient which is the combination of reliability and capacity factors. The replaceable neighboring states and minimum set of neighboring states are defined and the number of computations and comparisons is significantly reduced. The system studies show that the computation time of reliability evaluation is reduced and the accuracy of the reliability indices is increased. For the same number of system states to be considered, the performance of the FCST is better than the FSA.

Among the five severity coefficients, \( \varphi_j^1(a) \) provides the most accurate reliability results. The severity coefficient \( \varphi_j \) with considering only availability usually provides the less accurate results than the other four severity coefficients. It can be concluded that the severity coefficients with considering capacity factor are suitable for power system reliability evaluations and the FCST can rapidly determine the most severe states from all the contingency states.

### REFERENCES


