A bulk power system reliability assessment methodology

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SUMMARY

This paper describes a methodology for the reliability evaluation of bulk power systems. The method encompasses the systematic enumeration of contingencies and the evaluation of their effects on the system over a range of system load levels. Contingencies and electric load levels are described with Markov models. Reliability indices are computed using these models. Both an adequacy approach and a simplified security approach are considered in the effects analysis. The overall framework of the proposed methodology is capable of considering the full security approach but it is not addressed in this paper. In the adequacy approach, an improved system simulation method is used based on the single-phase quadratized power flow (QPF). Remedial actions (RAs) are also applied for the purpose of alleviating system abnormal operating conditions. The adequacy approach determines whether the system is adequate for supplying the electric load without operating constraint violations. In the simplified security approach, the immediate response of the system is of interest. The simulation approach consists of an inertial re-dispatch and operating conditions immediately after a contingency before any controls take effect. The objective is to determine whether cascading failures occur. The proposed methodology has been applied to two reliability test systems. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: reliability assessment; bulk power system; adequacy; security; remedial actions; quadratized power flow; reliability indices

1. INTRODUCTION

Bulk power system reliability assessment has received considerable interest in recent years [1–10]. There are two reasons for this interest: (1) planners are faced with the challenge to produce sound designs of power systems with minimum possible transmission capacity margins and (2) there is pressure from consumer groups and regulatory agencies to justify building new system facilities. Reliability models for the bulk power system provide an attractive tool to system planners to meet these demands. Specifically, a reliability analysis model is useful for (1) comparative evaluation of expansion

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plans, (2) justification of transmission additions, (3) cost/benefit analysis of expansion plans, (4) estimation of interruption costs, (5) review of maintenance schedules, and so on.

Methods for the bulk power system reliability analysis are classified into two categories, namely the Monte Carlo simulation and the enumerative methods.

The Monte Carlo simulation [3–9] consists of randomly selecting the state of system components and the state of the load and subsequently simulating contingency effects. The basic approach can be applied for each hour in a year in a chronological order (the sequential approach) or the hours of the study time can be considered at random (the random approach). The simulation of randomly selected system conditions is done with the use of load flows, dispatch algorithms, and pre-selected operating policies. The simulation results are statistical distributions of variables of interest (circuit flows, voltage levels, energy curtailment, and so on). These results are utilized in the computation of appropriate reliability indices. In order to speed up the convergence of the simulation procedure, various techniques, including state space pruning [6,7], parallel processing [8], and variance reduction [9], have been applied.

In the enumerative method [1–3,10], the fact that the majority of component outages do not cause service curtailment or other adverse impact on service reliability is recognized. Thus, the enumerative method focuses on identifying the outage events, which may have adverse effects on the reliability of electric service, and then analyzing these events to quantify their effects. The primary steps of this approach are (1) the identification of outage events that may lead to unreliability and (2) the simulation of these outage events to determine their impact on system reliability. Obviously, the simulation of outage events is a common component of both Monte Carlo and enumerative methods.

This paper describes a methodology for the bulk power system reliability assessment based on the enumerative method. The proposed method is based on a systematic enumeration of contingencies and the evaluation of their effects for a range of system load levels. Three different classes of reliability indices are computed: (a) probability indices, (b) frequency indices, and (c) duration indices. In the effects analysis, both adequacy and security approaches are provided to determine the system adequacy as well as security after contingencies. Recent blackouts have brought into focus the need for this type of reliability analysis. This methodology is illustrated in two example test systems: (a) a 10-bus power system and (b) the IEEE 24-bus reliability test system.

2. METHODOLOGY

This section describes the proposed methodology for bulk power transmission system reliability assessment. The overall computational algorithm is illustrated in Figure 1, which mainly includes three steps: (1) state enumeration, (2) effects analysis, and (3) reliability index computations.

System states (contingencies) and electric load states are generated from Markov models of system components and electric load levels. Specifically, each component (circuit or unit) is modeled with a two-state Markov model, that is, the component is either working (up) or failed (down). The electric load is modeled as a nonconforming load model. This model relates bus loads to a small set of independent random variables. The discretization of independent random variables provides discrete load states that are described with an equivalent Markov model, where each load level is characterized with probability and transition rates to any other load levels. In addition, each bus load is separated into interruptible, firm, and critical components and associated with a voltage dependency assumed as follows: for the normal range of the bus voltage, the load is constant; for values below the normal voltage range, the load is dependent upon the voltage with a linear relationship.
2.1. State enumeration

The state enumeration involves (1) the enumeration of contingencies, including independent circuit and unit outages as well as common-mode outages and (2) the enumeration of electric load levels.

2.1.1. Contingency enumeration. The objective of contingency enumeration is to identify the contingencies that may lead to unreliability. Since the complete evaluation of all the contingencies is impractical, the enumeration is based on the use of a hybrid contingency ranking scheme [11]. The additional truncation of contingencies can be obtained by truncating the depth level of contingencies and by neglecting contingencies with very small probabilities.

Generally, contingency ranking methods may be classified into two categories: (a) Performance Index (PI) methods [12–14] and (b) screening methods [11]. It is well known that PI approaches are fast but prone to misranking. On the other hand, screening methods are more accurate but inefficient. The hybrid contingency ranking scheme separates contingencies into two sets with certain rule [11]: (a) contingencies with mild nonlinearities and (b) contingencies with potentially high nonlinearities. The first set of contingencies represents the majority and is ranked by PI based methods with multiple PIs. The second small set of contingencies is ranked with screening methods. In this work, the quadratized power flow (QPF) model is applied in PI methods. QPF has milder nonlinearities (by construction) and therefore performs better in improving the ranking accuracy than the traditional power flow model.
[15–17]. Also, computational savings are achieved by applying screening methods only to a small set of contingencies.

In Figure 2, a wind-chime enumeration scheme [10,18] illustrates the contingency enumeration procedure using the ranking order obtained by the hybrid ranking method. The procedure starts with a base case. All the first level contingencies are enumerated and ranked in the decreasing severity order. The second outage level contingencies are obtained from each contingency in the first outage level by having one more component on outage and ranked in the same way. At any level, the contingency list includes independent outages as well as common-mode outages. In addition, the contingency list is so generated as to make sure the obtained contingencies are distinct and there is no double counting. This procedure continues until it reaches the predefined depth level or probability criteria of contingencies. In each outage level, the contingency evaluation starts from the most severe contingency. If there are several successive contingencies that are evaluated but have zero contribution to system unreliability, then it is reasonable to conclude that the rest of the contingencies in the list under consideration need not to be investigated. Figure 2 shows these three types of contingencies, they are (1) contingencies that are evaluated and have nonzero contribution to unreliability, (2) contingencies that are evaluated but have zero contribution to unreliability, and (3) contingencies that are not evaluated.

2.1.2. Electric load enumeration. Electric load levels are modeled with a multi-state Markov model. The load states are created from a nonconforming load model. Specifically, this load model is described with a small set of independent random variables. The discretization of independent random variables provides discrete load states that are described with an equivalent Markov model, where each load level is characterized with a probability and transition rate to any other load levels. The so defined electric load states are enumerated within the proposed algorithm as it is shown in Figure 1.

2.2. Effects analysis

Each combination of contingency and load level is analyzed to determine the effects on system performance. The system performance is measured with a set of pre-specified criteria using QPF and remedial actions (RA)s if necessary. Failure criteria include: (a) circuit overloads, (b) bus under-voltage

Figure 2. Wind-chime enumeration scheme.
and over-voltage, (c) the curtailment of interruptible load, (d) the curtailment of firm load, (e) the curtailment of critical load, and so on.

In the effects analysis process shown in Figure 1, two approaches are available: (a) adequacy and (b) security. Both approaches are briefly described below.

2.2.1. **Adequacy evaluation approach.** The objective of the adequacy evaluation is to determine whether the system is capable of supplying the electric load under the specified contingency. For this purpose, the QPF and RAs module (without load shedding capability) determine whether the system is adequate. If not RAs with load shedding capability are applied to determine where and how much load shedding will be needed to alleviate emergencies. A concise description of these tools follows.

2.2.1.1. **Quadratized power flow model** QPF model is set up by applying the Kirchhoff’s current law at each bus, and state variables are expressed in Cartesian coordinates [19]. Subsequently, the equations are quadratized, that is, they are expressed as a set of equations that are linear or quadratic. This formulation is void of trigonometric terms, which makes power flow equations less complex. The formulation of the quadratic power flow provides superior performance in two aspects: (a) faster convergence and (b) ability to model complex power system characteristics in the quadratized form.

2.2.1.2. **Remedial actions** RAs provide means of correcting system abnormal operating conditions, such as alleviating circuit overloads and abnormal voltages. A list of system typical RAs is given in Table I, which also includes an indication of the relative cost associated with each RA. The quadratized RA model accommodates the RAs of Table I in an effort to determine system adequacy [17]. The control variable $u$ is defined for each RA device to represent the availability and magnitude of these control actions. The required RAs under each contingency are computed via an optimization model as follows:

$$\min f(x, u)$$

subject to:

$$g(x, u) = 0$$

$$h_1_{\text{min}} \leq h_1(x, u) \leq h_1_{\text{max}}$$

$$u_{pi_{\text{min}}} \leq u_{pi} \leq u_{pi_{\text{max}}}$$

<table>
<thead>
<tr>
<th>Remedial action</th>
<th>Relative cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Shunt capacitor switching</td>
<td>Low</td>
</tr>
<tr>
<td>2 Shunt reactor switching</td>
<td>Low</td>
</tr>
<tr>
<td>3 Phase shifter adjustment</td>
<td>Low</td>
</tr>
<tr>
<td>4 MVAR generation adjustment</td>
<td>Low</td>
</tr>
<tr>
<td>5 Generation bus voltage</td>
<td>Low</td>
</tr>
<tr>
<td>6 Transformer taps</td>
<td>Low</td>
</tr>
<tr>
<td>7 FACTS controls</td>
<td>Low</td>
</tr>
<tr>
<td>8 Load transfer</td>
<td>Low</td>
</tr>
<tr>
<td>9 MW generation adjustments</td>
<td>Moderate</td>
</tr>
<tr>
<td>10 Area interchange</td>
<td>High</td>
</tr>
<tr>
<td>11 Interruptible load</td>
<td>High</td>
</tr>
<tr>
<td>12 Firm load</td>
<td>High</td>
</tr>
<tr>
<td>13 Critical load</td>
<td>High</td>
</tr>
</tbody>
</table>
where

\( p \): RA type as listed in Table I.
\( i \): RA device number.
\( u_{pi} \): RA control variable with type \( p \) and device number \( i \).
\( u_{pi}^{\text{min}}, u_{pi}^{\text{max}} \): RA control variable’s lower and upper bounds.
\( u \): vector of RA control variables.
\( x \): vector of system states.
\( h_l(x, u) \): operating constraint expression.
\( h_l^{\text{min}}, h_l^{\text{max}} \): operating constraint’s lower and upper bounds.

Equation (1): objective functions, which can be defined as the minimum amount of RAs, and so on.
Equation (2): QPF equations.
Equation (3): operating constraints.
Equation (4): feasible region of RA control variables.

The solution method for the above problem is iterative and includes two steps in each iteration:
(a) the linearization of the objective function and operating constraints and (b) the solution of the resulting linear programming problem. The co-state method [16,17] is employed in the linearization of the optimization problem to compute sensitivities of the objective function and operating constraints with respect to each control variable \( u_{pi} \). This linearization procedure results in an optimization problem of the linear programming variety. The simplex method or the interior point method [20] has been used to solve this problem.

Therefore, the adequacy evaluation approach determines whether the system is adequate in supplying the electric load without operating constraint violations. In case of inadequacy, RAs will involve load shedding, which is recorded as a system failure. Results of contingency evaluations are stored and subsequently used by the reliability calculation model to calculate reliability indices.

2.2.2. Security evaluation approach. The aim of this approach is to determine whether the immediate response of the system will generate potential problems for system reliability. This is a simplified security approach which focuses on the immediate response of the system via an inertial re-dispatch and the effects of reduced voltage on loads. Full transient response is not considered. Specifically, the simulation approach considers the system conditions during the fault that generates the contingency and consists of an inertial re-dispatch and operating conditions immediately after the contingency and before any controls take effect. The objective is to determine whether cascading failures may occur. This approach encompasses the quasi-transient performance of the system after contingencies.

2.3. Reliability indices

Reliability indices are computed on the basis of identifying the set of states that satisfy a specific failure criterion and the transition rates from any state inside the set to a state outside the set. Figure 3 shows a state space diagram, including the evaluated and nonevaluated states (contingencies). A contingency \( j \) at certain load level is characterized with a certain probability \( p_j \) and transition rates to and from other system states, such as \( \lambda_{jk} \) and \( \lambda_{ij} \). An event \( S_n \), which contains a set of evaluated states that possess some common features such as system failure states, is identified by retrieving the stored results of effect analysis. Three different classes of reliability indices then can be computed: (a) probability, (b) frequency, and (c) duration indices.
2.3.1. Probability index. The probability of $S_r$ is obtained by adding all the contingency probabilities in set $S_r$:

$$P_r[S_r] = \sum_{j \in S_r} p_j$$

(5)

where

$p_j$: probability of contingency (state) $j$, which is the multiplication of the probability of each component working status (up or down) obtained from the component Markov model.

Note that all the states in the set are mutually exclusive by construction. The probability of event $S_r$ equals the sum of the state probabilities.

2.3.2. Frequency index. The frequency of event $S_r$ is the total of the transition frequency of a state $j$ inside $S_r$ to a state $i$ outside $S_r$, therefore,

$$f_{S_r} = \sum_{i \notin S_r} \sum_{j \in S_r} f_{ji} = \sum_{i \notin S_r} \sum_{j \in S_r} p_j \lambda_{ji} = \sum_{i \notin S_r} \left( \sum_{j \in S_r} p_j \lambda_{ji} \right)$$

(6)

where

$\lambda_{ji}$: transition rate from state $j$ to state $i$.

$f_{ji}$: frequency of transfer from state $j$ to state $i$, which is defined as the expected number of direct transfers from $j$ to $i$ per unit time. The relation between $f_{ji}$ and $\lambda_{ji}$ can be written as following:

$$f_{ji} = \lambda_{ji} p_j$$

(7)

2.3.3. Duration index. The duration index of event $S_r$ is calculated using the probability index and the frequency index:

$$T_{S_r} = \frac{P_r[S_r]}{f_{S_r}}$$

(8)

Considering that not all the contingencies are evaluated, we assume that unevaulated contingencies belong to a set $N$. It is apparent that some of them will be failures and some will be successful. Therefore, it is possible to compute upper and lower bounds [21] on the probability by applying the extreme conditions: (a) all the states in $N$ are successful and (b) all the states in $N$ are failures.
As a result:

\[ P_r[S_r]^u = \sum_{j \in (S_r + N)} p_j \quad (9) \]

\[ P_r[S_r]^l = \sum_{j \in S_r} p_j \quad (10) \]

where \( S_r + N \) means the union of the sets \( S_r \) and \( N \), and the probabilities of unevaluated states in set \( N \) can be obtained similarly as those evaluated states as shown in Equation (5).

The computation of upper and lower bounds for frequency and duration indices related to the determination of all the transition rates from failure states to success states. This procedure should be repeated for each frequency index which uses a different failure criterion.

3. CASE STUDIES AND RESULTS

The methodology described in the preceding sections has been applied to a 10-bus power system and the IEEE 24-bus reliability test system [22]. The first level independent outages and common-mode outages have been considered. In the effects analysis, the adequacy evaluation is performed. Appropriate RAs are computed and applied whenever operating constraint violations occur.

The 10-bus power system is shown in Figure 4. It consists of 10 buses, 12 circuit branches, 5 generators, and 3 loads. Generator 1 is designated as the slack generator. Generators 2, 3, and 5 are in PQ mode. Generator 4 is in PV mode. RAs of this system include the re-dispatch of the active power of generators 2, 3, 4, and 5 and the reactive power of generators 2, 3, 5, as well as load shedding. Three loads at Buses 30, 40, and 90 include interruptible load that forms part of RAs.

Figure 4. A 10-bus power system.
A partial list of evaluated contingencies is given in Table II. Contingencies from 1 to 6 are common-mode outage events. Contingencies from 7 to 17 are independent outage events. The remedial action computation procedure is illustrated by contingency 10 (the outage of line 70–30). The outage of transmission line 70–30 generates under-voltages at Buses 30 and 40, or the following active constraints that are violated:

\[
\frac{U_{30}}{C_{21}} \leq U_{30,\text{min}} \tag{11}
\]
\[
\frac{U_{40}}{C_{21}} \leq U_{40,\text{min}} \tag{12}
\]

The optimization model is formulated by considering the minimum RAs as the objective function. The sensitivity values of bus voltages \(U_{30}\) and \(U_{40}\) with respect to RAs are calculated by the co-state method [16,17]. The linear programing solutions of RAs are provided as following:

\[
\Delta Q_1 = 72 \text{ MVAr}
\]
\[
\Delta Q_5 = 77.61 \text{ MVAr}
\]

Updating the RAs and solving the quadratic power flow, the new set of active constraints are:

\[
U_{30} \geq U_{30,\text{min}} \tag{13}
\]
\[
U_{40} \geq U_{40,\text{min}} \tag{14}
\]
\[
U_{81} \leq U_{81,\text{max}} \tag{15}
\]

It should be noted that the constraints (13) and (14) are not violated anymore, but they are active and it is necessary to be retained in the problem formulation. The constraint (15) is the new active constraint.

<table>
<thead>
<tr>
<th>No</th>
<th>Outage components</th>
<th>Constraint violations (Yes/No)</th>
<th>RAs without load shedding (Yes/No)</th>
<th>Load shedding (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T10–20, G1, G2</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>TL30–40, L40</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>TL70–90, L90</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>TL20–30, TL20-30</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>T70–80, G4</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>T70–81, G5</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>TL20–30</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>TL20–70</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>TL50–70</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>TL30–70</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td>TL50–60</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>12</td>
<td>T60–30</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>13</td>
<td>G3</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>14</td>
<td>G1</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>G2</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>16</td>
<td>G4</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>17</td>
<td>G5</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

T, transformer; TL, transmission line; G, generator.

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resulting from the updated RAs. Based on this new set of active constraints, the solution of the optimization model yields:

\[ \Delta P_3^2 = 25.448 \text{ MW} \]
\[ \Delta P_4^2 = 6.959 \text{ MW} \]
\[ \Delta Q_5^2 = -16.832 \text{ MVAr} \]

Upon implementation of the RAs, all the operating constraints are satisfied. The remedial action computation procedure is then finished. The accumulated total remedial action is the sum of RAs at each iteration:

\[ \Delta P_3 = 25.448 \text{ MW} \]
\[ \Delta Q_3 = 72 \text{ MVAr} \]
\[ \Delta P_4 = 6.959 \text{ MW} \]
\[ \Delta Q_5 = 60.778 \text{ MVAr} \]

Since all the operating constraint violations are eliminated by RAs without load shedding, this result shows that contingency 10 has zero contribution to system unreliability, or the system is adequate. Other contingencies are similarly evaluated. The evaluation results of whether there are constraint violations and the need of RAs with or without load shedding are shown in Table II.

Reliability indices are calculated and given in Table III for both situations with and without RAs.

The second test system is the IEEE 24-bus reliability test system, composed of 24 buses, 38 circuits, and 32 generators [22]. The system peak load level is applied. RAs contain the re-dispatch of the active and reactive power of generators that are working in PV or PQ mode, a synchronous condenser, switching off a reactor, and shedding loads. The first level contingencies resulting from independent and common-mode outages are evaluated. Reliability indices with and without RAs are computed based on the evaluation results and shown in Table IV.

It can be seen from Tables III and IV that the reliability indices with RAs are much lower than that without RAs. This is due to the reason that when RAs are not taken into account in the adequacy evaluation, contingencies that lead to constraint violations are considered to have nonzero contribution to system unreliability. However, when RAs are incorporated, only the contingencies involving load

<table>
<thead>
<tr>
<th>Table III. Reliability indices of 10-bus system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>With RAs</td>
</tr>
<tr>
<td>Service failure probability</td>
</tr>
<tr>
<td>Service failure frequency</td>
</tr>
<tr>
<td>Service failure duration</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table IV. Reliability indices of IEEE 24-bus reliability test system.</th>
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<tbody>
<tr>
<td>With RAs</td>
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<td>Service failure probability</td>
</tr>
<tr>
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</tr>
<tr>
<td>Service failure duration</td>
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</tbody>
</table>
shedding are considered to have nonzero contribution to system unreliability. The differences in the reliability indices of the two power systems demonstrate the significant effect of RAs on the reliability assessment.

4. CONCLUSIONS

A comprehensive method for assessing the reliability of bulk power systems has been described. The method is based on a state enumeration, the evaluation of post contingency system conditions after appropriate RAs, and the calculation of reliability indices for a number of failure criteria. A system simulation method based on QPF model is adopted to improve the accuracy of contingencies ranking and increase the efficiency of effects analysis. Both the adequacy and security evaluation algorithms for the power system reliability are provided. In adequacy approach, RAs are computed to take into account the effects of realistic operator actions. The applications of the adequacy approach on two test power systems are presented and evaluation results show the influence of RAs on system reliability.

Note that for the two test systems presented in this paper only the evaluation on the first level contingencies is reported and for a single load level using adequacy approach. This is necessary to keep the presentation complexity manageable. The methodology is applicable to any level of contingencies and any number of load states. The security approach is based on an oversimplified approach to determine the risk of cascading events. Future work will focus on more sophisticated security assessment models.

5. LIST OF SYMBOLS AND ABBREVIATIONS

\( f(x, u) \)  objective functions
\( g(x, u) \)  quadratized power flow equations
\( h_j(x, u) \)  operating constraint expressions
\( h_{l_{\text{min}}} \)  operating constraint’s lower bounds
\( h_{l_{\text{max}}} \)  operating constraint’s upper bounds
\( u_{pi} \)  remedial action control variable with type \( p \) and device number \( i \)
\( u_{pi_{\text{min}}} \)  remedial action control variable’s lower bound
\( u_{pi_{\text{max}}} \)  remedial action control variable’s upper bound
\( u \)  vector of RA control variables
\( x \)  vector of system states
\( \lambda_{ji} \)  transition rate from state \( j \) to state \( i \)
\( p_{j} \)  probability of contingency \( j \)
\( f_{ji} \)  frequency of transfer from state \( j \) to state \( i \)
\( S_{r} \)  an event represents system unreliability
\( P_{r}[S_{r}] \)  probability index of event \( S_{r} \)
\( f_{S_{r}} \)  frequency index of event \( S_{r} \)
\( T_{S_{r}} \)  duration index of event \( S_{r} \)
\( P_{r}[S_{r}]^{u} \)  upper bound on the probability of event \( S_{r} \)
\( P_{r}[S_{r}]^{l} \)  lower bound on the probability of event \( S_{r} \)
\( P \)  generator real power output
\( Q \)  generator reactive power output

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REFERENCES

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