TRANSMISSION SYSTEM RELIABILITY ANALYSIS IN POWER SYSTEMS RELIABILITY INSTRUCTION

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Abstract

Identification of the appropriate reliability indices and the means of evaluation of these indices is one of the basic procedures in power systems reliability education. The reliability indices are usually based on the continuity of service to the consumer, the unreliability effects on losses. All of these indices can, however, be derived from three dimensions of reliability: frequency, duration and magnitude. This concept along with an appropriate software package that is written for a PC environment can be utilized in determining the reliability of power systems in a reliability engineering course. The concept and the computer program have been tested on an actual system and the results are presented in this paper.

1 Introduction

There is a growing interest in the quantitative assessment of power system reliability and many of available techniques are taught in either graduate or undergraduate courses. Quantitative reliability assessment should consider not only the actual physical elements in a system in terms of their function and random behavior but also recognize overall system operating requirement, deterministic policies and other engineering considerations. The calculated indices should be easily understood and interpreted. There is a wide range of techniques and resulting indices available and used in the assessment of engineering systems. Presently, there is no consensus within the electric power industry on what constitutes a complete set of adequacy indices for system reliability evaluation. Many reliability indices and software programs have been utilized in reliability analysis of large scale power systems transmission systems [1]. A few software packages that evaluate the composite reliability, i.e., both transmission and generation systems, of power systems have been developed in recent years.

There are several power systems reliability indices which are based on the continuity of service to the consumer, the quality of power supply, the unreliability effects on price, the unreliability effects on losses, etc. As a result, the reliability of a system is measured by indices such as Bulk Power Energy Curtailment, Bulk Power Supply Average, Bulk Power Interruption Index, Probability of Failure (LOLE), Frequency of Failure, Expected Load Curtailed, Energy Not Supplied (LOEE), Expected Duration of Load, Average Number of Curtailment/Load Point/Year [2]. The most common probabilistic criteria are the loss of load expectation (LOLE) and the loss of energy expectation (LOEE).

In the formal instruction of the subject of power system reliability evaluation and the investigation which was conducted for electric utilities at Tulane University over the past four years, studies have been concentrated on identification of reliability indices that are suitable for measurement of the effect of unreliability on continuity of power supply to consumers. It is understood that all of the indices mentioned above are based on three fundamental terms which are sometimes referred to as the three dimensions of reliability. The three terms, Frequency, Duration, and Magnitude, can be utilized to derive other reliability indices.

This concept can prove useful in teaching the reliability engineering courses and in obtaining a physical appreciation of the indices derived by these three terms. This paper presents some results and additional indices for IEEE Reliability Test System [3] obtained using this simple and direct concept which provide valuable information on the random behavior of the system. The object of this paper is to present...
three dimensional concept in power systems reliability education and illustrate how this concept can be used to derive other reliability indices and provide a physical insight into the random behavior of the power systems.

2 Definitions and Description

There are three basic reliability terms which are sometimes called the three dimensions of reliability. All other terms and indices of performance are based on some combination of these three basic quantities. They are:

\[ F = \text{Occurrences per unit of time of the undesirable event (frequency)} \]

\[ D = \text{Mean duration per occurrence of the undesirable events occurring in a unit of time (duration)} \]

\[ M = \text{Mean magnitude or severity of the undesirable events occurring in a unit of time (magnitude), normal units are MW, KW, or customers)} \]

In this paper, the undesirable event will be assumed to be an outage of consumer service. Unless otherwise specified, the unit of time considered is a year.

If frequency of outage in occurrences per year is multiplied by mean duration of outage in a year, the product is total per unit expected duration of outage in a year which is also the probability of outage in a year. So, frequency times duration is equal to probability.

In the approximate 45-year evolution of modern power system reliability development, the probability of outage has had many semi-formalized names, for instance, Loss of Load Expectation (LOLE), Probability of Negative Margin (PONM), Loss of Load Probability (LOLP), etc. The important point to remember about probability is that it is a product of two of the basic dimensions of reliability and in being a product conceals the individual magnitude of each of the basic dimensions. Furthermore, and perhaps more important, it neglects completely the dimension of magnitude of outage. As many planners have found when working with large power systems, the probability of outage is an adequate index for the iterative decisions that are necessary in arriving at a final plan for a complex system. However, granting that the use of the probability index arrives at the proper specific system modifications and additions, there still remains the stigma of having used an index that does not consider magnitude of outage. The planners of small utility systems probably should not use probability as a planning index because total system outages are more likely and should be especially weighted in the studies.

This disadvantage of probability led to the introduction of the index which is the product of frequency times duration times magnitude. When frequency in expected outages per year is multiplied by the mean expected duration of outage and the mean expected magnitude of outage in megawatts, the expected energy loss in megawatt hours is derived. This index is frequently called the Loss of Energy Expectation (LOEE), Loss of Energy Probability (LOEP), Expected Unserved Energy (EUE), etc. The important thing to remember of this index is that even though it does include all of the basic dimensions and therefore conceals the individual magnitude of the individual dimensions.

The derivation of the expected energy not served (LOEE or EUE) when combined with the societal value of unserved energy will permit a global optimization to be performed which could be a powerful planning tool and regulatory authority communication medium. In this optimization, the economic value of unserved energy would be considered along with the other more normal costs of service to arrive at the particular system plan which has the lowest societal cost. The expected energy not served and the industrial and commercial costs associated with the frequency of outage would be the key ingredients in this optimization.

A common relationship resulting from this explanation is that LOEE divided by LOLE equals M (the mean magnitude of the undesirable event).

If the magnitude of the three individual dimensions of unreliability is known, various system and load point indices can be computed as follows [2]:

a. Annualized load point indices:

\[ \text{Probability of Failure (LOLP)} = \sum_{j \in \mathbb{N}} P_j P_{K_j} \]  
(1)

\[ \text{Frequency of Failure} = \sum_{j \in \mathbb{N}} F_j P_{K_j} \]  
(2)

\[ \text{Expected Load Curtailed} = \sum_{j \in \mathbb{N}} M_{K_j} F_j MW \]  
(3)

\[ \text{Expected Energy Not Supplied (LOEE)} = \sum_{j \in \mathbb{N}} M_{K_j} D_{K_j} F_j MW \]  
(4)

\[ \text{Expected Duration of Load Curtailment} = \sum_{j \in \mathbb{N}} D_{K_j} F_j \text{hours} \]  
(5)

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b. Annualized system indices:

\[ \text{BulkPowerEnergyCurtailmentIndex or Severity Index} = \sum_{K \in \Sigma} \sum_{j \in \Sigma_j} P_j F_j K_j M_{K_j} F_j \frac{M_{K_j} D_{K_j}}{M_{\text{sys}}} \text{MW curtailment/disturbance} \] (6)

\[ \text{BulkPowerSupplyAverage} = \frac{\sum_{j \in \Sigma_j} M_{K_j} F_j}{\sum_{j \in \Sigma_j} F_j} \text{MW/MW yr} \] (7)

\[ \text{BulkPowerInterruptionIndex} = \frac{\sum_{j \in \Sigma_j} M_{K_j} F_j}{M_{\text{sys}}} \] (8)

where \( j \) is an outage condition in the network; \( P_j \) is the probability of existence of outage \( j \); \( F_j \) is the frequency of occurrence of outage \( j \); \( F_{K_j} \) is the probability of the load at bus \( K \) exceeding the maximum load that can be supplied at that bus during the outage \( j \); \( j \in \Sigma \) includes all contingencies resulting in line overloads which are alleviated by load curtailment at bus \( K \); \( j \in \Sigma_j \) includes all contingencies which result in an isolation of bus \( K \); \( M_{K_j} \) is the load curtailment at bus \( K \) to alleviate line overloads arising due to the contingency \( j \), or the load not supplied at an isolated bus \( K \) due to the contingency \( j \); \( D_{K_j} \) is the duration in hours of the load curtailment arising due to the outage \( j \), or the duration in hours of the load curtailment at an isolated bus \( K \) due to the outage \( j \); \( M_{\text{sys}} \) is the total system load.

The proceeding indices are the more commonly used reliability indices.

3 Case Study

A power system model is composed of various components such as generators, lines, transformers and loads. A generating unit can be represented by a two state model or a multi-state such as the three-state model. The operating cycles of a unit can be simulated using the state residence time distributions. The state residence times are assumed to be exponentially distributed. The system available capacity model can be obtained by combining the operation cycles of all units. The system operates at certain times at reduced capacity levels due to forced outages of some generating units.

The application of the proposed methodology will be illustrated with The IEEE Reliability Test System (RTS) [3], as shown in Figure 1. The total installed capacity in the RTS is 3405MW. The total system load in the RTS is 2850MW. The RTS load data and generating unit reliability data are shown in Table 1 and Table 2.

When the Generator No.1 (50.0MW) at bus 22, No.12 (155.0MW) at bus 15 and No.28 (155.0MW) at bus 23 are out of service, there is no load curtailment. The frequency and duration for this event are 0.004498/yr and 7.870 hours, respectively.

Table 3 illustrates what occurs when Generator No.29 (350.0MW) is out of service instead of Generator No.28 with the rest of data remaining same. The frequency and duration for this event are 0.008292/yr and 8.910 hours, respectively.

Having the magnitude of the three individual dimensions of unreliability for each contingency, the annualized load point indices and system indices can be obtained by using formula (1)-(8). The following is the results of system indices.

\[ \text{BulkPowerEnergyCurtailmentIndex} = 35.52773 \text{MW h/MW yr} \]

\[ \text{BulkPowerSupplyAverage} = 136.78217 \text{MW curtailment/disturbance} \]

\[ \text{BulkPowerInterruptionIndex} = 2.26318 \text{MW/MW yr} \]

4 Conclusions

This paper illustrates the increasing importance of quantitative assessment of power system reliability and utilization of the basic concept - three dimensions of reliability - in power systems reliability education. A range of basic studies on The IEEE Reliability Test System using the three dimensional concept are presented. Results similar to what is presented in this paper can be obtained from the simulation programs that are available in the market. In references [4,5] several existing software packages have been compared and utilized for their practicality as a tool for probabilistic transmission and generation planning reliability analysis.

The concept of three dimensions of reliability provides a physical appreciation of capacity deficiencies and the interaction of the available capacity with the load model. This basic concept can be used effectively in teaching quantitative assessment in a graduate or undergraduate power system program.
Acknowledgements

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References


Table 1: RTS BUS LOAD DATA

<table>
<thead>
<tr>
<th>Bus</th>
<th>Load MW</th>
<th>MVAR</th>
<th>Voltage kV</th>
<th>% of System Load</th>
</tr>
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<tr>
<td>1</td>
<td>108</td>
<td>22</td>
<td>138</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>97</td>
<td>30</td>
<td>138</td>
<td>24</td>
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<tr>
<td>3</td>
<td>189</td>
<td>30</td>
<td>138</td>
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<tr>
<td>4</td>
<td>74</td>
<td>15</td>
<td>138</td>
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</tr>
<tr>
<td>5</td>
<td>71</td>
<td>15</td>
<td>138</td>
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</tr>
<tr>
<td>6</td>
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<td>8</td>
<td>117</td>
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<tr>
<td>10</td>
<td>117</td>
<td>35</td>
<td>138</td>
<td>20</td>
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<tr>
<td>Subtotal</td>
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<td>348</td>
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<td>60.1</td>
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Table 2: RTS GENERATING UNIT RELIABILITY DATA

<table>
<thead>
<tr>
<th>Unit Size MW</th>
<th>Number of Units</th>
<th>Forced Outage Rate(5)</th>
<th>MTTR(1) hrs.</th>
<th>MTTR(2) hrs.</th>
<th>Scheduled Maintenance wee/year</th>
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<tr>
<td>12</td>
<td>5</td>
<td>0.02</td>
<td>2940</td>
<td>60</td>
<td>2</td>
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<td>20</td>
<td>4</td>
<td>0.10</td>
<td>400</td>
<td>60</td>
<td>2</td>
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<tr>
<td>60</td>
<td>6</td>
<td>0.01</td>
<td>1800</td>
<td>40</td>
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<tr>
<td>75</td>
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<td>1800</td>
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<td>2</td>
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<tr>
<td>100</td>
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<td>0.04</td>
<td>1200</td>
<td>60</td>
<td>3</td>
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<tr>
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<td>5</td>
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<td>400</td>
<td>2</td>
<td>0.12</td>
<td>1100</td>
<td>150</td>
<td>6</td>
</tr>
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</table>

NOTES:
(1) MTTF = mean time to failure
(2) MTTR = mean time to repair
(3) Forced outage rate = MTTF / MTTF + MTTR

Table 3: Load Point Indices of Contingency

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Load Curtailed (MW)</th>
<th>Energy Curtailed (MWh)</th>
<th>Frequency (per week)</th>
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</thead>
<tbody>
<tr>
<td>13</td>
<td>11.87</td>
<td>0.0994</td>
<td>0.877</td>
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<td>15</td>
<td>14.20</td>
<td>0.1177</td>
<td>1.049</td>
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<td>16</td>
<td>4.49</td>
<td>0.0372</td>
<td>0.331</td>
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<tr>
<td>20</td>
<td>5.73</td>
<td>0.0475</td>
<td>0.424</td>
</tr>
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Total = 36.27 0.3008 2.880