Abstract—EPRI has developed a Probabilistic Risk/Reliability Assessment (PRA) method under Power Delivery Reliability Initiative, which has been successfully implemented by various energy companies in planning studies of growing complexity. Unlike the traditional deterministic contingency analysis, PRA combines a probabilistic measure of the likelihood of undesirable events with a measure of the consequence of the events (that is, the impact) into a single reliability index – Probabilistic Reliability Index (PRI). EPRI internally developed the PRI program that uses contingency analysis results as well as the transmission facility outage information as input to compute and graphically display the reliability indices. This paper presents an application of PRI program to study the transmission network of New York Power Authority (NYPA). This work has demonstrated that the PRA method significantly improves the ability of conducting effective transmission operational planning. The paper represents the collaborative effort between EPRI and NYPA.

Index Terms – Operational Planning, Probabilistic Risk Assessment.

I. INTRODUCTION

Electric system reliability is always one of the most important concerns in power system operations and planning. As the power industry undergoes its fundamental restructuring, energy markets are created to allow fair and competitive energy trading for all the market participants. The inter-regional bulk power transfers can vary dramatically and the energy transactions among parties change frequently. The electric power grid is continuously stretched beyond its means, i.e., what the grid was originally designed for. Meanwhile, customer expectations of reliability are rising to meet the needs of a pervasively digital world. Maintaining the reliability becomes more challenging than ever before for the grid operations and planning.

EPRI worked with a number of energy companies to develop and test a technique known as Probabilistic Risk Assessment (PRA) [1-3] to perform risk-based reliability assessment. Unlike traditional deterministic methods, PRA calculates a measure of the probability of undesirable events and a measure of the severity or impact of the events. Based on PRA method, EPRI developed a Probabilistic Reliability Index (PRI) program. The PRI program offers the energy industry a more accurate tool for assessing grid reliability under restructured market conditions.

PRA has already been used by many utilities since 2001 and sufficient data is now available for the power industry to move toward wide-spread implementation of the methodology. So far, EPRI has performed PRA studies for Southern Company, American Electric Power, Tri-State Generation and Transmission Company, Kansas City Power & Light[4], the Eastern Interconnection, and ERCOT. Over ten utilities are adopting the PRA method and are beginning to use it for their own studies.

In 2006, EPRI performed a risk assessment study of the entire New York State power system with more focus on NYPA’s transmission network. The objective of the study is to help NYPA operations planners identify potential failure modes by taking into account both probabilities of contingencies and their physical impacts, in order to design a more robust transmission system and assist NYPA decision makers to prioritize transmission projects by balancing reliability and risk.

This paper presents the application results of PRA study for NYPA. The paper is organized as follows: Section II reviews the probabilistic risk assessment methodology. In Section III, the study data preparation and assumptions are described. Section IV presents the study results. In Section V, the study conclusions are summarized.

II. PROBABILISTIC RISK ASSESSMENT METHODOLOGY

Operating the transmission system is like navigating a ship, as shown in Figure 1. Operators need to know where the problem is located, how likely it is going to happen, and how much operating margin they have. Reliability assessment should work like radar to give notice of danger and its proximity. The traditional deterministic contingency analysis does not recognize the unequal probabilities of events that lead to potential operating security limit violations. PRA combines a probabilistic measure of the likelihood of undesirable events with a measure of the consequence of the events (that is, the impact) into a single reliability index – Probabilistic Reliability Index (PRI).
EPRI internally developed PRI program which uses contingency analysis results as well as the transmission facility outage information as inputs. It then computes and displays the reliability indices. Figure 2 shows the computation architecture of PRI program. EPRI has developed application program interfaces (API) with many existing commercial contingency analysis programs such as Siemens/PTI MUST, PSS/E IPLAN, GE PSLF EPCL, and V&R POM.

PRI is defined as the product of an impact by a probability.

\[
PRI = \text{Out\_Probability} \times \text{Impact}
\]  

where the Out\_probability quantifies the likelihood of the simulated outage configuration, and the physical impact quantifies the severity of the situation.

The impacts and the reliability indices are of four distinct types: APRI (amperage or thermal overload), VPRI (voltage violation), VSPRI (voltage instability) and LLPRI (load loss):

- **Overload Reliability Index :**
  \[
  \text{APRI} = \sum_{i\in\text{[Simulated\_Situations]}} \text{Out\_probability}_i \times \text{Aimpact}_i
  \]  
  where Aimpact\_s is the thermal overload above the branch thermal rating caused by the ith critical situation. The thermal overload impact is measured in terms of MVA or KA.

- **Voltage Reliability Index :**
  \[
  \text{VPRI} = \sum_{i\in\text{[Simulated\_Situations]}} \text{Out\_probability}_i \times \text{Vimpact}_i
  \]  
  where Vimpact\_s is the voltage deviation from the bus upper and lower limits caused by the ith critical situation. The voltage impact is measured in terms of kV or p.u..

- **Voltage Stability Reliability Index :**
  \[
  \text{VSPRI} = \sum_{i\in\text{[Simulated\_Situations]}} \text{Out\_probability}_i \times \text{VSim}\text{impact}_i
  \]  
  where VSim\text{impact}_s is the voltage stability impact caused by the ith critical situation. It is measured in binary format. If a situation causes the system becoming voltage unstable, the voltage stability impact value of is equal to 1. Otherwise, it is equal to 0.

- **Load Loss Reliability Index :**
  \[
  \text{LLPRI} = \sum_{i\in\text{[Simulated\_Situations]}} \text{Out\_probability}_i \times \text{LLimpact}_i
  \]  
  where LLimpact\_s is the total load loss caused by the ith critical situation. The load loss impact is measured in MW.

In a planning context, probability is a measure of the likelihood that the power system will be in a given situation at a random time in the future, and is a function of the availability of every piece of equipment in the power system.

\[
\text{Out\_probability} = \prod_{i\in\mathcal{U}} u(c_i) \prod_{j\in\mathcal{A}} a(c_j)
\]  

where \( U \) represents the set of unavailable components; \( A \) represents the set of available components; \( \Omega = U \cup A \), \( \Omega \) represents the complete set of system components. \( u(c_i) \) and \( a(c_j) \) represent the unavailability and availability rates of the component \( i \), respectively.

It is not realistic that all outages are independent because there are always the cases where transmission lines share the same towers; generating units share the common devices; pieces of equipment are connected without breakers etc. In those cases, the outage of several elements may have a common cause (or common mode). In PRA methodology, we define a group of components that systematically experience outages at the same time for a common cause as common mode failure. Once identified, the common mode failure is modeled as a single availability rate from the outage point view.

EPRI has developed six types of analyses and implemented them into PRI program. The six types of analyses can be divided into two categories: system level analyses and component level analyses.
**Overall Analysis** indicates the reliability level of the entire system. The overall reliability index can be calculated by adding the four types of reliability indices: APRI, VPRI, VSPRI and LLPRI.

**Interaction analysis** unveils the cause and effect relationship among user-defined zones. Zone interaction is defined by a zone “cause” where the outage is located and a zone “affected” where the violations are experienced. Each interaction is named as “by Zone_Cause on Zone_Affected. by Zone1 on Zone2” means that the violations encountered in Zone 2 were caused by outages in Zone 1.

\[
PRI(\text{Zone1 on Zone2}) = \sum_{\text{Situation Zone1}} \sum_{\text{Component Zone2}} PRI(\text{Situation, Component})
\]

**Probabilistic margin analysis** establishes the relationship between reliability indices with stress level. It provides a measure for system robustness. Margin is a measure of the distance to danger zones. Probabilistic margin analysis answers the question of “how far I can go with a given direction starting from base case before entering into trouble”. The direction could be load level, transfer level or generation output etc.

**Situation analysis** ranks the situation according to their contribution to the index. It helps the user to identify the scenarios that have high probability or high impact or both. The situation analysis results are displayed in Probability/Impact space as shown in Figure 6.

**Root cause analysis** indicates the facilities (line, transformer, generator etc) that cause a critical situation. A root cause facility is a facility (i.e., line, transformer, and generator) that experiences an outage and creates a critical violation, whether or not it is combined with other outages. The root cause reliability index is defined as follows:

\[
PRI(\text{RootCause}) = \sum_{\text{Situation, RootCause}} PRI\left(\sum_{\text{order(RootCause)}}\right)
\]

where PRI(Situation) is the Probabilistic Reliability Index of all of critical situations that involve this root-cause facility; k represents the number of situations that involve the root-cause facility.

The index of each situation is equally shared among the contributing root causes. The root cause probability is the probability that the outage of the facility causes a violation whether or not combined with other outages.

**Weak point analysis** identifies the buses and branches that most violated. A weak point component is a component (bus or branch) that experience at least one violation. The weak point reliability index is defined as:

\[
PRI(\text{WeakPoint}) = \sum_{\text{Situation, Affecting the WeakPoint}} PRI(\text{Situation, WeakPoint})
\]

The index is associated with a list of critical situations that cause violations on the weak point components.

**III. STUDY DATA AND ASSUMPTION**

NYPA provided EPRI the New York ISO 2010 summer power flow base case. This studied system includes 46785 buses, 28035 loads, 7756 generators, 55175 transmission lines, 17752 transformers, and 3621 switched shunts.

**A. Description of Contingency Analysis**

NYPA provided the technical requirements for the contingency assessment including:

1) A voltage constraint file that specifies voltage limits. This voltage constraint requirement is applied to all buses 100 kV and above in Areas 1-11 (New York State Areas).
2) A thermal constraint file that specifies 100% of Summer Rating as thermal limit for all branches 115 kV and above in Areas 1-11 (New York State Areas).
3) A contingency list that consists of 759 single or multiple contingencies. From this, EPRI performed contingency analysis and identified 144 critical contingencies.
B. Description of Probability Data

Generic outage probability data are used for this study. The generic probability file contains the parameters that enable to compute unavailability rates of various power system components.

As an example, the unavailability rate of a line is estimated using the following equation:

\[ u = \frac{\text{Outage Freq} \times \text{Repair Time}}{8760} \]  

(7)

In the above equation, the outage frequency is estimated using the following equation:

\[ \text{Outage Freq} = a + b \times \left( \frac{Z}{Z_{\text{puPerMile}}} \right) \]  

(8)

where \( a \) (1/year): is the constant parameter of the forced outage frequency, \( b \) (1/year/mile): is the proportional parameter of the forced outage frequency, \( Z_{\text{puPerMile}} \) (pu/mile): is the average impedance (p.u.) per mile used to estimate the line length, RepairTime (hour): is the average repair time (hour) after a forced outage.

IV. APPLICATION OF PRA METHOD TO SYSTEM STUDIES

The PRI program can perform both deterministic and probabilistic risk assessment, which allows system operators and planners to compare the two methodologies.

A. Overall Analysis

PRI has the capability to display the overall analysis results in bar chart and tabular format, as shown in Figure 7.

![Fig. 7. Displaying the overall analysis results](image)

According to probabilistic analysis, Area 7 is the most critical area in terms of voltage violations, and contributes 74% to the overall probabilistic voltage reliability index. Area 7 is also the most critical area in terms of thermal violations. It contributes 37% to the overall probabilistic thermal overload reliability index.

According to deterministic analysis, Area 10 is the most critical area in terms of voltage violations. It contributes 55% to the overall deterministic voltage reliability index. Area 7 is the most critical area in terms of thermal overloads. It contributes 28% to the overall deterministic thermal overload reliability index.

B. Interaction Analysis

PRI has the capability to display the interaction analysis results in tabular format and on the regional geographic map, as shown in Figure 8. When displaying the interaction analysis results of voltage violation on a regional geographic map, each bubble represents a control area. The PRI value inside the bubble shows the reliability index when both the contingencies and the impacts happened in this control area. Each arrow with the PRI value indicates the interaction from the Zone_Cause where the contingencies occurred to the Zone_Affected where the impacts happened.
According to probabilistic interaction analysis of thermal violations, Area 7 is the most critical cause and the most severely affected area. According to deterministic interaction analysis of thermal violations, Area 4 is the most critical area and Area 7 is the most severely affected area. Table 3 and Table 4 display the probabilistic and deterministic interaction analysis results in tabular format.

### Table 3
**Probabilistic Interaction Analysis of Thermal Violations (11 Control Areas)**

<table>
<thead>
<tr>
<th>Area</th>
<th>WEST</th>
<th>NORTHERN</th>
<th>CENTRAL</th>
<th>NORTH</th>
<th>MIDDLE</th>
<th>CAPITOL</th>
<th>MILLWOOD</th>
<th>DAVINCO</th>
<th>NYC</th>
<th>L. ISLAND</th>
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<tbody>
<tr>
<td>Area 7</td>
<td>0.250</td>
<td>0.125</td>
<td>0.625</td>
<td>0.571</td>
<td>0.429</td>
<td>0.625</td>
<td>0.250</td>
<td>0.125</td>
<td>0.875</td>
<td>0.750</td>
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<tr>
<td>Area 4</td>
<td>0.000</td>
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<td>Area 10</td>
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### Table 4
**Deterministic Interaction Analysis of Thermal Violations (11 Control Areas)**

<table>
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<tr>
<th>Area</th>
<th>WEST</th>
<th>NORTHERN</th>
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<td>0.250</td>
<td>0.125</td>
<td>0.875</td>
<td>0.750</td>
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<td>Area 4</td>
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**C. Situation Analysis**

PRI has the capability to display the situation analysis results in bubble diagram and tabular format, as shown in Figure 9. According to probabilistic situation analysis of voltage violations, outage of a 345/138 kV transformer in Area 7 is the most critical contingency with consideration of both probability and impact. According to deterministic situation analysis of voltage violations, 'SBK: MOSE_115' is the most critical contingency causing severe voltage violations.

According to probabilistic situation analysis of thermal violations, outage of a 230 kV line in Area 5 is the most critical contingency with consideration of both probability and impact. According to deterministic situation analysis of thermal violations, 'TWR: MWP& PV20' is the most critical contingency causing severe thermal violations.

**D. Root cause analysis**

PRI has the capability to display the root cause analysis results in bubble diagram, tabular format or component map, as shown in Figure 10.

According to probabilistic root cause analysis of voltage violations, a 345/138 kV transformer in Area 7 is the most critical root cause facility with consideration of both outage probability and impact. According to deterministic root cause analysis of voltage violations, a 240/120 kV Autotransformer in Area 4 is the most critical root cause facility whose outage will cause the most severe voltage violations.

According to probabilistic root cause analysis of thermal violations, a 230 kV line in Area 5 is the most critical root cause facility with consideration of both outage probability and impact. According to deterministic root cause analysis of thermal violations, a 345 kV line in Areas 6 and 7 is the most critical root cause facility whose outage would cause the most severe overload violations.
E. Weak Point Analysis

PRI has the capability to display the weak point analysis results in bar chart, tabular format or component map, as shown in Figure 11.

According to probabilistic weak point analysis of voltage violations, a 138 kV Bus in Area 7 is the weakest bus with consideration of both violation probability and impact. According to deterministic weak point analysis of voltage violations, a 115 kV Bus in Area 4 is the weakest bus in terms of voltage violation impact.

According to probabilistic weak point analysis of thermal violations, a 115 kV line in Area 7 is the weakest branch with consideration of both the violation probability and impact. According to deterministic weak point analysis of thermal violations, the same 115 kV line in Area 7 is the weakest branch in terms of thermal violation impact.

V. CONCLUSIONS

In this paper, probabilistic risk assessment on the New York transmission network using EPRI PRI program is presented. EPRI PRI program offers the power industry a powerful tool to perform risk-based reliability assessment. PRI program provides a comprehensive risk assessment in both a deterministic and a probabilistic way. The study

- assessed overall system reliability;
- unveiled the cause and effect relationship among user-defined areas;
- ranked the contingencies according to their contribution to the reliability indices;
- identified the transmission system components most likely to contribute to critical situations;
- identified the specific branches and buses most susceptible to interruption.

Performing probabilistic risk assessment enables NYPA system planners to receive complimentary information in addition to the traditional deterministic contingency analysis results. Displaying deterministic and probabilistic risk assessment results on charts, tables and maps, enables the visualization of complex reliability information effectively.

The study would help NYPA system planners visualize their system reliability and its interaction with neighboring control areas. It could also help recognize the critical situations that have both high probability and high impact, and develop effective remedial action schemes to mitigate these contingencies. In addition, the study could help NYPA system planners identify the root cause and weak point facilities so that they can be monitored closely during system operation. Ensuring the reliable operation of these facilities would significantly improve the reliability of the entire transmission system.

VI. REFERENCES


VII. BIOGRAPHIES

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