Abstract - The traditional methods of industrial and commercial power system reliability studies can be enhanced by the use of Six Sigma methods. The goal of the Six Sigma approach is to improve the quality of a process by reducing the number of “defects.” In electrical systems defects are defined as outages. The method begins by determining which aspects of the process are “critical to quality,” and then uses a systematic approach to reduce variation in the process to reduce the failure rate. Finally, monitoring and control procedures are put in place to ensure continuing quality. This approach is well suited to systematizing the distribution reliability study.

INTRODUCTION

Reliability assessments of electric power distribution systems can be conducted by analysis of system data and by calculation of reliability indices using statistical techniques, such as the minimal cut set method and reduction of series and parallel networks. The analysis is then utilized in order to identify trends in the overall maintenance and operation of a system, to determine which components are in need of upgrading or replacement, and to aid in the design of a new or redesigned power system, IEEE (1).

The Six Sigma methodology was developed as a tool for quality control programs in manufacturing operations, with the goal of reducing the variance of selected product attributes, Smith (2), Pande (3). Six Sigma techniques have been adapted to processes where the outcome can be measured only in binary form, the presence or absence of a defect. Under the title of "Design for Six Sigma," Six Sigma techniques have also been used for improving the design of new systems and equipment.

The term "sigma" refers to the “distribution or spread about the mean (average) of any process or procedure,” Harry (4). The process being evaluated must be both stable and normally distributed. In processes with outputs that have continuously measurable attributes, there will be a process mean and standard deviation, as well as lower and upper tolerance limits. A defect is defined as occurring when a measured attribute is outside the tolerance limits. Using the standard normal or Z distribution, the “sigma” is calculated as:

\[ Z = \frac{X - \mu}{\sigma} \]

Z is the number of standard deviations (σ), the tolerance limit X is from the mean μ.

For a measure such as failures per year used with electrical distribution systems, the data is discrete. The process data for each category of output consists of the number of defects, the number of units and the number of opportunities per unit. From this is determined the number of defects per opportunity (DPO) and the number of defects per million opportunities (DPMO). The probability that there will not be a failure is:

\[ P(0) = 1 - \frac{1}{DPO} \]

The Six Sigma calculation procedure is to find the number of standard deviations between the mean and the cumulative standard normal distribution of P(0), using (1), and a the correction factor for short-term process variation, often assumed to be 1.5. A process with 3.4 DPMO has 6.0 sigma short-term variation. Reduction of variation is accomplished by reducing the number of defects.

CONCLUSIONS

The performance of plant reliability studies can be enhanced by the use of Six Sigma methods, bringing improvements to the study procedures and results. A firm methodology for evaluation of the existing system, creation of a baseline, and a structured search for improvements that both improve reliability and lower operating costs is followed. This procedure uses the same techniques used in standard study procedures, such as described in the Gold Book. The usage of the techniques is systematized, reducing the possibility of overlooking an alternative or of proposing a solution that is not cost-effective. The use of the Six Sigma terminology may aid in the presentation of reliability study results to an audience that is not familiar with the concepts of power system reliability studies.

* A longer version of this paper will be presented at the 2001 IEEE Industrial and Commercial Power Systems Technical Conference.
ASSESSMENT OF INDUSTRIAL DISTRIBUTION SYSTEM RELIABILITY USING SIX SIGMA METHODOLOGY*

P E Sutherland

GE Power Systems Energy Consulting, USA

Abstract - The traditional methods of industrial and commercial power system reliability studies can be enhanced by the use of Six Sigma methods. The goal of the Six Sigma approach is to improve the quality of a process by reducing the number of “defects.” In electrical systems defects are defined as outages. The method begins by determining which aspects of the process are “critical to quality,” and then uses a systematic approach to reduce variation in the process to reduce the failure rate. Finally, monitoring and control procedures are put in place to ensure continuing quality. This approach is well suited to systematizing the distribution reliability study.

Index terms: power system reliability, six sigma.

INTRODUCTION

Reliability assessments of electric power distribution systems can be conducted by analysis of system data and by calculation of reliability indices using statistical techniques, such as the minimal cut set method and reduction of series and parallel networks. The analysis is then utilized in order to identify trends in the overall maintenance and operation of a system, to determine which components are in need of upgrading or replacement, and to aid in the design of a new or redesigned power system, IEEE (1).

The Six Sigma methodology was developed as a tool for quality control programs in manufacturing operations, with the goal of reducing the variance of selected product attributes, Smith (2), Pande (3). Six Sigma techniques have been adapted to processes where the outcome can be measured only in binary form, the presence or absence of a defect. Under the title of "Design for Six Sigma," Six Sigma techniques have also been used for improving the design of new systems and equipment.

The term "sigma" refers to the “distribution or spread about the mean (average) of any process or procedure,” Harry (4). The process being evaluated must be both stable and normally distributed. In processes with outputs that have continuously measurable attributes, there will be a process mean and standard deviation, as well as lower and upper tolerance limits. A defect is defined as occurring when a measured attribute is outside the tolerance limits. Using the standard normal or Z distribution, the “sigma” is calculated as:

\[ Z = \frac{(X - \mu)}{\sigma} \]

Z is the number of standard deviations (σ), the tolerance limit X is from the mean μ.

For a measure such as failures per year used with electrical distribution systems, the data is discrete. The process data for each category of output consists of the number of defects, the number of units and the number of opportunities per unit. From this is determined the number of defects per opportunity (DPO) and the number of defects per million opportunities (DPMO). The probability that there will not be a failure is:

\[ P(0) = 1 - DPO \]

The Six Sigma calculation procedure is to find the number of standard deviations between the mean and the cumulative standard normal distribution of P(0), using the equation for Z, above, and a correction factor for short-term process variation, often assumed to be 1.5. A process with 3.4 DPMO has 6.0 sigma short-term variation. Reduction of variation is accomplished by reducing the number of defects.

The purpose of conducting a distribution system reliability study using Six Sigma techniques is twofold: first to provide a structure and a standardized set of procedures for performing the study, and secondly to be able to present the results in a commonly understood framework. Although the goal of achieving a reduction of defects to 3.4 parts per million may seem distant, the focused nature of a Six Sigma reliability assessment can lead to significant increases in power system reliability.

A typical electrical distribution system may have an overall sigma of approximately 3.5. The outage rate at an individual substation will be less, resulting in a higher sigma for each load delivery point. Incremental improvements by replacing aging equipment and making some design changes may increase the sigma a small amount. Major improvements, such as adding redundant sources can increase the overall plant sigma to the range of 4 to 5. Using these procedures, the electrical power system is improved in the manner that yields the greatest increase in reliability with the least cost of implementation.

* A longer version of this paper will be presented at the 2001 IEEE Industrial and Commercial Power Systems Technical Conference, Sutherland (8).
STUDY PROCEDURE AND RESULTS

Define

The "Critical to Quality" (CTQ) parameters are selected. Failures in the 13.8 kV distribution system at the facility result in outages to critical production facilities and computer systems. Outages are measured in terms of two critical to quality (CTQ) parameters:

- Major failures per year, \( \lambda \)
- Average hours downtime per failure, \( r \)

It is the goal of this study to determine means to reduce these two measures of outages.

The business case is made by obtaining data on the cost of outages in downtime and lost production. The expected benefits of this project include increased available production time, reduction of downtime due to outages, reduced repair and rework costs, and reduced damage to equipment. These are summarized in Table 1.

<table>
<thead>
<tr>
<th>Substation MVA Capacity</th>
<th>Revenue lost per hour of plant downtime</th>
<th>Variable expenses saved, per hour of plant downtime</th>
<th>Variable expenses incurred per failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical 1</td>
<td>$25,737</td>
<td>$18,708</td>
<td>$64,342</td>
</tr>
</tbody>
</table>

The process is defined using the electrical one-line diagram. The power flow is from the utility source at 115 kV to the 13.8 kV distribution buses. The process consists of the electrical distribution system, composed of transformers, cables, buses, circuit breakers, and other equipment. A typical plant one-line diagram is shown in Figure 1.

Measure

The CTQ parameter to be improved is selected to be \( \lambda \), the number of failures per year. Determination of the Critical to Quality (CTQ) parameters requires consultation with the customers, in this case, end-users of the electrical power.

The defect definition is chosen to be the failure in the electrical distribution system that will cause an outage. A unit is defined as the point of service for a customer load, in this case a 13.8 kV distribution substation. An opportunity is defined as one component-year. In some discussions of reliability, a unit is an individual equipment, such as a circuit breaker, transformer, or standard length of cable for which reliability data is available, Nelson (5).

In this case, the CTQ parameter is defined as an outage, not the failure of a particular equipment. This is because the reliability study is customer focused, rather than supplier focused. If the system has redundancy, not all failures of equipment will result in an outage. Only failures which result in an outage are significant to the end-user of the power.

On the other hand, the number of opportunities for a failure to occur is determined by the number of distribution system components serving a particular customer. These components consist of transformers, buses, circuit breakers, cables, lines and other distribution equipment. The exposure of each individual component to failure over a period of one year is considered to be an opportunity.

The failure rate is a measure of the number of failures per unit-year. The defect rate, expressed as Defects per
Million Opportunities (DPMO) is derived from the failure rate on a standardized basis.

Data is gathered on the outages in the existing system, and tabulated into outages per year per equipment type. The downtime data is also gathered, if available. The data are checked for statistical validity and confidence limits are established. The outage data available was data concerning the failure of individual equipments and feeders, not outages at the load buses. The downtime at a typical load bus was calculated using a reliability analysis program.

The outage data is converted to the failure rate by dividing the number of equipment failures observed by the number of unit-years over which the survey was conducted, IEEE Committee Report (6):

\[ \hat{\lambda} = \frac{f}{T} \]

where \( \hat{\lambda} \) is the estimated equipment failure rate per unit-year (the actual failure rate being \( \lambda \)), \( f \) is the observed number of equipment failures, and \( T \) is the number of unit-years over which the survey was conducted. It is recommended in the Gold Book that a minimum of eight to ten equipment failures be used when computing failure rates.

In order to determine whether the calculation of the equipment failure rate yields a usable value, the confidence limits of the data are checked. The equipment failure rate has a Poisson distribution (6). In this example, only the feeder cable data was usable. The outage rate at a typical distribution load bus was calculated using a reliability analysis program.

The calculated outage rate was found to be 0.400 Defects per Unit (DPU). For a distribution system with 200 components, the Defects per Opportunity (DPO) is \( 2.0 \times 10^{-3} \). The Defects per Million Opportunities (DPMO) for each year is calculated to be \( 2.0 \times 10^{3} \).

Before determining the “sigma,” the process must be determined to be stable. The stability of the process can be determined by analyzing the number of occurrences of failures over time. The usual technique is to plot a “run chart” (Figure 2) of the outages per year.

The next step for most processes is to test for normality, and determine whether the process fits a normal probability curve. In this instance, the occurrence of failures is known to follow a Poisson Distribution. There exists a Normal Approximation of the Poisson Distribution (5):

\[ F(y) = \Phi \left( \frac{y + 0.5 - \mu}{\sqrt{\mu}} \right) \]

where \( \Phi \) is the standard normal cumulative distribution function. The mean is \( \mu = \bar{y} \), the average number of failures per opportunity, and the standard deviation is \( \sqrt{\mu} \). This approximation is said to be valid when the expected number of failures exceeds 10 failures/year, but the validity can be checked for any particular combination of \( y \) and \( \mu \). However, it is proposed that this approximation may be made valid over a wider range of \( y \) and \( \mu \) by replacing 0.5 by a constant \( k \):

\[ F(y) = \Phi(y + k) \]

where \( F(0) \) is the cumulative Poisson distribution for \( y = 0 \). For example, if there are 0.0020 failures/opportunity over a period of 1 year, \( \mu = 0.0020 \times 1 \times 1 = 0.0020 \).

\( k = 0.1307 \)

\[ F(0) = \Phi \left( \frac{0 + 0.1307 - 0.0020}{\sqrt{0.0020}} \right) \]

The probability of zero failures in a year is:

\[ F(0) = \Phi(2.88) = 0.9980 \]

This can be compared with the Poisson Distribution of \( \mu = 0.002 \) being 0.9980. These results are shown in Figure 3 for failure rates of up to 4 occurrences per year. This approximation gives results that are very close to the standard normal distribution for instances where the \( \mu \) is small.

The probability of a defect for a normally distributed function can be determined from the standard normal curve. For example, if there are \( 2.0 \times 10^{-3} \) DPO, the probability of zero failures is:

\[ P(0) = 1 - DPO = 1 - 0.0020 = 0.9980 \]

The “sigma” is:

\[ z_{LT} = \frac{y + k - \mu}{\sigma} \]

where \( z_{LT} \) is the “long term” process variation

\( k \) is the constant = 0.1307

\( y \) is the specification limit = 0

\( \mu \) is the mean number of failures = 0.002,

\( \sigma \) is the standard deviation = \( \sqrt{\mu} \).

From the formula above, or looking in a standard normal curve area table, if the area under the curve is \( P(0) = 0.9980 \) then \( z_{LT} = 2.88 \).

The short-term “sigma” is found by adding 1.5 to the \( z_{LT} \):

\[ z_{ST} = z_{LT} + 1.5 = 2.88 + 1.5 = 4.38 \]
A reliability study of the existing system is performed using reliability data previously collected, supplemented by published sources as necessary. The results of this study are compared to the failure rates determined from the data collection.

The base capability of the distribution system is determined by performing a reliability analysis of the existing system using reliability data from published industry sources.

Using the reliability study results, the existing equipment whose lower reliability than the norm has the greatest impact on the overall system reliability is identified. There is no significant difference in the calculated outage rate for this substation with the actual or the typical equipment outage rate used.

Preliminary reliability runs are performed to identify which equipments may be replaced, and which portions of the system may be redesigned, in order to increase reliability.

A Design of Experiments (DOE) procedure is used to identify additional reliability runs to perform. The results are analyzed for correlation between system reliability and the various proposed changes in system and equipment. The results are listed in Table 2. The greatest decrease in outage rate occurs with the upgrading of the 115 kV switchgear. The reason for this is the great difference in failure rates for 115 kV OCBs and SF6 circuit breakers (1).

The proposed changes in the system and equipment are analyzed further to convert failures/year to defects per opportunity and thus to Sigma. They are also analyzed in terms of cost avoidance with improved reliability versus cost of making improvements to the system. From these results, recommendations are made for changes in the system to improve reliability.

A comparison of calculated Sigma for an example system is shown in Table 3. There is little difference between the existing system and a system with all equipment brought up to industry average reliability, or if the upgrades to the system are made. Cost calculations (not shown) show that making no changes is the second most cost effective measure, while replacing the 115 kV substation is the most cost effective measure.

### TABLE 2 Correlation coefficients for recommended improvements.

<table>
<thead>
<tr>
<th></th>
<th>115 SG</th>
<th>13.8 SG</th>
<th>Feeder</th>
<th>13.8 Sub</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outage Rate</td>
<td>-0.99554</td>
<td>-0.05894</td>
<td>-0.01791</td>
<td>-0.04241</td>
</tr>
<tr>
<td>Downtime</td>
<td>-0.99956</td>
<td>-0.02003</td>
<td>-0.003</td>
<td>-0.01903</td>
</tr>
</tbody>
</table>

### TABLE 3 Calculated Improvement of System Reliability According to Six Sigma Measures

<table>
<thead>
<tr>
<th>Process</th>
<th>Defects</th>
<th>Units</th>
<th>Opportunities</th>
<th>Long Term Capability</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>0.4000</td>
<td>1</td>
<td>200</td>
<td>2.88</td>
<td>4.38</td>
</tr>
<tr>
<td>Base Case</td>
<td>0.4000</td>
<td>1</td>
<td>200</td>
<td>2.88</td>
<td>4.38</td>
</tr>
<tr>
<td>Improvements</td>
<td>0.3200</td>
<td>1</td>
<td>200</td>
<td>2.92</td>
<td>4.42</td>
</tr>
<tr>
<td>Redundancy</td>
<td>0.0020</td>
<td>1</td>
<td>200</td>
<td>4.27</td>
<td>5.77</td>
</tr>
<tr>
<td>Utility</td>
<td>0.2630</td>
<td>1</td>
<td>1</td>
<td>0.73</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Explanation of column headings:
1. These are the case conditions from the study.
2. Defects are outages per year at the load.
3. Units are points of service for load.
4. Opportunities are the number failure points in the system.
5. Long Term Capability, $z_{LT}$, is from standard normal table.
6. “Sigma” is Short Term Capability, $z_{ST}$. A shift of 1.5 sigma is assumed between the long term and short term capabilities.

In order to achieve higher levels of reliability, cases were run comparing these results with the addition of cogeneration at the 13.8 kV distribution substation, or supplying the distribution substation from a separate utility source. These results are also shown in Table 3. The cost evaluations show that a separate utility source is cost-prohibitive, while cogeneration is one of the most expensive options when compared to the 16 already considered. The greatly increased reliability of cogeneration, coupled with additional savings possible
due to steam generation may make it the most reasonable choice.

**Control**

These steps are to be performed after the planned upgrade of the power system:

A power monitoring system is installed, if one is not already present. Outage data from this system is gathered and checked for validity.

A reliability study is performed on the as-built system using published reliability data, in order to determine the process capability.

A maintenance management system is implemented, where equipment and systems having greater than expected failures are identified and corrective action is taken.

**CONCLUSIONS**

The performance of plant reliability studies can be enhanced by the use of Six Sigma methods, bringing improvements to the study procedures and results. A firm methodology for evaluation of the existing system, creation of a baseline, and a structured search for improvements that both improve reliability and lower operating costs is followed. This procedure uses the same techniques used in standard study procedures, such as described in the Gold Book. The usage of the techniques is systematized, reducing the possibility of overlooking an alternative or of proposing a solution that is not cost-effective. The use of the Six Sigma terminology may aid in the presentation of reliability study results to an audience that is not familiar with the concepts of power system reliability studies.

**References**