A Review of the Reliability of Electric Distribution System Components: EPRI White Paper

Technical Report

A Review of the Reliability of Electric Distribution System Components: EPRI White Paper

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REPORT SUMMARY

This report discusses available literature, data, and models related to the reliability of electric power distribution system components and discusses the influence of environmental factors and testing results on component reliability. It also critiques the value of this information for value of service studies.

Background

EPRI has been developing methods for distribution planning since 1992. At that time, research directed at the concept of distributed resources begun by EPRI, Pacific Gas & Electric (PG&E), and the National Renewable Energy Laboratory (NREL) led to further consideration of distribution planning in general. More recently, this analysis has raised the issue of an aging distribution infrastructure and how to optimize maintenance and replacement of aging systems.

Objectives

To document what is known about reliability of individual distribution system components as they age and to determine whether sufficient information exists to perform the required reliability analysis of aging distribution systems.

Approach

A detailed literature survey, described in the report, created a Reliability Data Library, a tool intended to support further development of models and methodology. The Reliability Data Library can be used by utilities to locate component reliability data and information on other topics related to the reliability of aging components.

Results

The literature review found extensive data available on the reliability of individual components. With cautious use, this data can provide the basis for system reliability analyses. However, reliability is greatly influenced by maintenance and environmental factors that are unique to individual utilities. This report's key finding is that it is extremely important that individual utilities track their individual component reliability so that over time they can understand the unique reliabilities of their installed components. There is no single, generally available dataset that distribution planners can use to answer all questions associated with reliability-based planning.

EPRI Perspective

As distribution systems age, planners increasingly face repair, upgrade, and replacement decisions. The problem of aging assets has become more important because of the increasing emphasis on reliability, customer service, and cost reduction. The EPRI Distribution Aging Asset project is developing methodology, data, and software tools to help companies determine "maximum value," repair/replace strategies for existing distribution assets; generate business cases for investment and O&M decisions; evaluate risks; and, focus manpower on high-value solutions.

The project began in 2000 and a Research Status Report was published. That report (EPRI report 1000422) describes research done to identify and develop analytical methods for making decisions about aging assets in electric distribution systems.

In 2001, the EPRI project team designed and implemented repair/replace software specifically tailored for electric distribution equipment. Extensive equipment failure research also was initiated. While that research will continue through mid-2003, two databases have been compiled—one contains equipment failure rate information and the other lists and summarizes equipment failure literature. Both of these databases are available on the website www.vmngroup.com and will be updated as new information becomes available. This research Status Report summarizes the 2001 Equipment Failure research.

Keywords

Reliability
Reliability of distribution systems
Failure rates
Hazard functions

ABSTRACT

This report describes data available on the reliability of electric power distribution system components. The document describes the data on failure rates and the data available on the change of failure rates with aging. It also discusses the qualitative impacts of maintenance, environment, and monitoring on the reliability of aging assets. The report is based on an extensive literature survey that investigated papers, reports, and books. The literature review found extensive data available on the reliability of individual components. With cautious use, this data can provide the basis for system reliability analyses. However, reliability is greatly influenced by maintenance and environmental factors that are unique to individual utilities. This report's key finding is that it is extremely important that individual utilities track their individual component reliability so that over time they can understand the unique reliabilities of their installed components. There is no single, generally available dataset that distribution planners can use to answer questions associated with reliability-based planning.

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1
INTRODUCTION

The key objective of the study was to determine whether sufficient published information exists to perform quantitative reliability analyses of aging distribution systems.

The study had a number of secondary objectives, including:

- To critique the current state of information on aging assets,
- To create a data base of information on the reliability of individual distribution system components as they age,
- To gather information on how environmental and maintenance differences can affect reliability,
- To gather information on how monitoring and testing can help in the determination of reliability,
- To identify how researchers have modeled the impact of aging on reliability, and
- To identify how information on individual component reliability can be used to support optimization of maintenance, monitoring, and replacement decisions.

This report presents the results of our study. It focuses on the available data related to the reliability of electric power distribution system components and the influence of environmental factors and testing results on component reliability.

What we looked at

The central purpose of our work was to determine and document the data available on the reliability of aging distribution system equipment. One author [Willis, 1997, p. 9] notes that transmission lines run voltages from 69kV to 1,100 kV and that distribution feeders run voltages of 2.2 kV to 34.5 kV. In general, we will define equipment running at 34.5 kV and below as distribution equipment and this will be the focus of our work. We do make exceptions for some distribution substation equipment that operate at voltages higher than 34.5 kV, in particular buswork, circuit breakers, and transformers.

Our primary approach to this task was via the published literature. We reviewed 191 publications, mostly journal articles and proceedings. The search for articles was conducted based on the following resources:

- The reference lists from earlier EPRI studies of distribution system reliability planning including Distribution System Reliability Handbook [Kostyal, 1982], Customer Needs for

Electric Power Reliability and Power Quality [Chapel, 2000(1)], Managing Aging Distribution System Assets [Chapel, 2000(2)], and Reliability of Electric Utility Distribution Systems [Chapel, 2000(3)];

- The reference list from a Canadian Electrical Association publication Guide to Value-Based Distribution Reliability Planning, Volumes I and II [Godfrey, 1996];
- An electronic search of publications dealing with electric power based on the key words: electric power and/or failure, common mode failure, loss-of-life and/or repair, replacement and/or distribution system, distribution system components, transformer, substation transformer, pole transformer, reclosers, switchgear, cable, conductor, underground cable, underground conductor, overhead cable, overhead conductor, overhead wire, capacitors, poles;
- A search of IEEE publications with a similar key word list;
- A search of the University of California library system on-line catalog; and
- References given by each paper reviewed.

What we produced

The study has produced three major products.

The largest and most significant product of the study is the database of articles. This database currently resides in Microsoft Excel and a copy also appears in Appendix A. As noted above, there are currently 191 entries. The database contains a complete reference for each article. It can be sorted based on reference characteristics such as Title, Publication Title (for publications from Journals and Proceedings), year of publication, and author. Publications are also classified by the component they deal with, a primary topic and a secondary topic and can be sorted by these classifications. The component classes are: System, Multiple, Generators, Cables, Capacitors, Poles, Switches, Transformers, Other, and Non-specific. Topic classes are: Financial Models, Technical Models, Causes of Failures or Wear, Discussions of Monitoring and Testing, Discussions of Design, Discussions of Maintenance and Replacement, Failure Rate Data, Failure Rate Equations, and Other.

The final fields in the database are the Summary and Notes fields. The Summary field provides an abstract or summary of what the publication covers. If the author has provided an abstract, we generally use that as a base and expand the description to cover aspects of the paper of particular interest to this study. The notes field is used for comments on the publication particular relevant to this study and most importantly to describe any data in the publication on reliability or failure rates. When available, we describe the origin of the data, the sample size, and the period over which it was collected. For each table of interest we describe the column and row headers and the entries in some detail. For each graph of interest, we describe the axes and the plotted data. We also include comments on the accuracy of the data, both those of the author and our own based on our review of the paper.

The second product of this effort is a summary database of the reliability data contained in the reviewed papers. This database is again in Microsoft Excel. The database is also found in

Appendix B. The rows of the database refer to individual distribution system components. These are grouped under: Buswork; Cables and Conductors; Cable and Conductor Connections; Capacitors; Poles; Switches, Circuit Breakers, and Fuses; Transformers and Other. The columns are divided into three sections.

The first section is simple failure rate data for the components. Units are failures/unit-year or failures/mile/year (for cable and conductor). Each column represents data from a single publication.

The second section contains data related to the impact of aging on reliability. Aging data include hazard rates. The hazard rate is the probability of a component failing over a short interval of time given that it has survived to a particular age. For example a 10-year old, pole-mounted transformer might have a hazard rate of 3.00E-03/year. Aging data about the components are summarized in five entries per source. These are: the source, hazard rate at 10 years, hazard rate at 20 years, hazard rate at 30 years and notes on the method of obtaining or calculating the hazard rates.

The third section contains data on the typical time to callout, isolate, and repair or replace components. Units are hours. Each column represents data from a single publication.

2
CLASSIFICATION OF PAPERS

As noted above, the database classifies the papers according to ten topics. For discussion it may be useful to distinguish four larger groups: publications dealing with failure causes, monitoring and maintenance; publications dealing with financial and technical modeling; publications dealing with data and failure equations; publications dealing with other topics.

About 25% of the publications deal with causes (7%), monitoring (12%), and maintenance (6%). We group these because they all deal with the hardware or the mechanics of failure. Many of these papers focus on a specific component. Transformers are by far the most thoroughly discussed.

Causes of failure or more rapid aging are:

- environmental - such as moisture, wind, ice, temperatures;
- use - such as loading, frequency, hours and
- maintenance - such as painting, tree clearing and fluid changes.

Publications in this area provide the reader with a qualitative understanding of how different circumstances will affect aging. In some cases, fairly specific recommendations are made on actions to reduce the impact of these causes of failure.

Many of the monitoring and maintenance papers provide substantial technical detail about monitoring or maintenance processes; and, many make specific recommendations on monitoring and maintenance regimens. However, with one exception [ABB Power T&D Company, 2001], none provide formulas that quantitatively relate monitoring or maintenance to failure rates or reliability.

45% of the papers discuss financial (19%) and technical (26%) modeling. These two approaches are distinguished by the objective function of the model. If the objective function is net benefit, usually measured in dollars, they are classified as financial. If the model is solely predictive of reliability, the publication is classified as technical. Some of these papers are purely theoretical. Many more present case studies or describe computer aids for financial or technical analysis. These papers are part of the literature that was the focus of earlier EPRI studies and papers, for example, *Distribution System Reliability Handbook* [Kostyal, 1982], *Managing Aging Distribution System Assets* Chapel, 2000(2)] and *Reliability of Electric Utility Distribution Systems* [Chapel, 2000(3)]. They expand upon the understanding of the state-of-the-art presented in those reports. The reports often provide failure rate data in the context of the case studies or examples presented.

A number of financial modeling papers specifically address value-based reliability planning or reliability centered maintenance.

23% of the papers are focused on reliability data or equations describing reliability. These are discussed in more detail in the next section.

The final 7% of the papers cover design (5 papers) and other topics (8 papers).

In addition to the reference database, we have gathered a Reliability Data Library, which is located at EPRI. This contains hardcopies of all the references described in the database except for a few books and reports that are held in the main EPRI library. Most of the hardcopy materials are copyright protected and have limitations on reproduction.

3
DATA

Overview

Figure 3-1: Typical Bathtub Curve of Failure Rates illustrates the failure pattern typically assumed for electric components. Early in their life, equipment experiences a high rate of failures often due to manufacturing or installation problems. There is then a long middle-life period of low and relatively stable failures due to random causes. Then equipment begins to wear out and aging causes the failure rate to accelerate. Depending on many factors discussed below, this failure pattern will differ for the same or similar components. Some will experience higher and lower than normal failure rates. We assume that when simple failure rates, stated as failures/year or failures/mile/year, are given, the failure rates refer to the failure rate during the long period of little change or a lifetime average that would be somewhat higher but generally close to the rate during a component's middle-life.

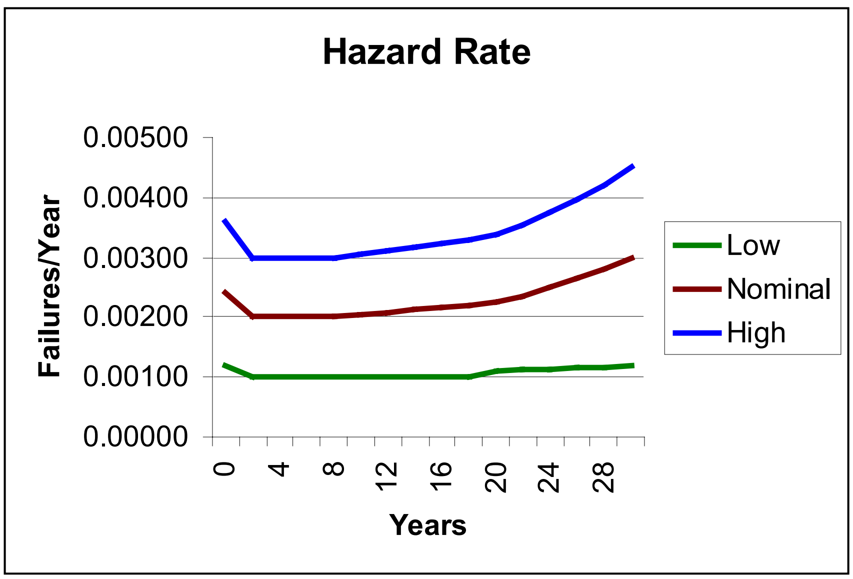

Figure 3-1
Typical Bathtub Curve of Failure Rates

The overwhelming bulk of the data are simple failure rates. Nineteen references present failure rate data that were included in our summary equipment database. Most of these present data on a number of components. Thirteen references provide data on the affects of aging on reliability that were included in our summary equipment database. Most of these deal with only one or two related components, for example, two types of underground cable.

A simple failure rate can be found for almost any (perhaps all) components in the distribution system. Failure rates for 82 components are provided. The references provide data for a still more detailed breakdown of components. Except for Buswork, at least one aging reference is available for all the major component areas: Buswork; Cables and Conductors; Cable and Conductor Connections; Capacitors; Poles; Switches, Circuit Breakers, and Fuses; Transformers; and Other. In this sense we have quite good coverage. Generally, if data is the focus of the publication, the sample size and dates of data collection are provided, but little else. Data from sources where modeling is the primary topic and data the secondary topic are generally not well documented. Those papers developing failure functions over time use a variety of methods and usually there are significant questions about their analysis methods.

Table 3-1: Summary of Failure Data presents data for seventeen components. Data is presented in much more detail in Appendix B. The low and high values in the table illustrate the range of simple failure rates for each component that we found in the literature. The 10 to 30 year multiple is an indication of the increase in failures with aging. The 10 to 30 year multiple is the failure rate for equipment that is 30 years old divided by the failure rate for equipment that is 10 years old.

This table starkly illustrates the very wide range of failure rates found in the literature. The high failure rate is frequently one, two, or three orders of magnitude greater than the low failure rate. An initial conclusion might be that data with this range of variation are of no value. We do not believe that this is an appropriate conclusion. We believe that it does indicate that each utility is unique and may experience very different failure rates. The data can be useful, but each utility must examine the underlying sources and determine which data are most likely to be appropriate for the utility's unique situation. The variance in the data and the apparent uniqueness of failure rates also suggest that each utility should initiate its own data collection program.

Table 3-1
Summary of Failure Data

	Failures/year		
Component	**Low**	**High**	**10 to 30yr Multiple**
Busbars	1.50E-03	1.10E-02	NA
Overhead conductor (per mile)	1.22E-02	1.80E+00	1.3
Underground cable (per mile)	7.35E-04	4.50E-01	2.7
Underground splices	1.00E-04	2.10E-03	6.5
Elbows	1.90E-04	1.50E-03	2.2
Capacitor Banks	8.50E-03	1.74E-01	21.4
Wooden Poles (one value)	3.34E-05	3.34E-05	38.3
Switches	1.50E-04	1.60E-01	3.1
Circuit breakers	2.00E-04	3.60E-02	1.2
Recloser	1.44E-03	1.50E-02	1.3
Fuses	8.70E-04	4.50E-03	1.0
Substation Transformers	1.50E-02	7.00E-02	NA
Pole-mounted Transformers	1.60E-05	4.40E-03	1.40
Pad-mounted Transformers	2.00E-03	4.50E-02	8.7
Submersible Transformers	1.38E-03	3.08E-03	1.5
Lightning Arrester	2.00E-04	1.32E-03	2.9
Voltage Regulator	2.88E-02	3.63E-02	NA

Table 3-2: Summary of Data Quality presents our qualitative judgments about the quality of the data for various components. Average quality means that there are multiple sources, at least one source is well documented, and that component definitions are appropriately detailed and clear. Below average indicates that there are few sources, data analysis or collection processes may be questionable, and/or definitions are unclear. Above average indicates multiple, well documented sources for the data.

Table 3-2
Summary of Data Quality

Component	Quality	Comments
Busbars	Below	Definitions uncertain
Overhead	Average	Several sources, some voltage differentiation
Underground	Above	Many sources, wide range of types of cable
Underground splices	Below	Little differentiation of types in data
Elbows	Average	Several sources, relatively high consistency
Capacitor Banks	Below	Few and uncertain sources
Wooden Poles	Below	Few sources
Switches	Below	Definitions uncertain, little differentiation of types in data
Circuit breakers	Average	Ok sources, wide range of types
Recloser	Average	Several sources, relatively high consistency
Fuses	Average	Assumed this is a simple component
Substation Trans	Below	Few sources, no aging data
Pole-mounted Trans	Above	Several reliable sources
Pad-mounted Trans	Above	Several reliable sources
Submersible Trans	Average	Average number of sources, some range of types
Lightning Arrester	Average	Assumed this is a simple component
Voltage Regulator	Below	One source

Problems

Problems with the data will be discussed under three headings: data gathering and reporting, component variability and the integration of monitoring data.

Problems are caused by limited information on the sources and methods of data collection and issues of definition. As noted above, many of the publications do not report fully the source of the data or details of the sample and data collection procedure. Equipment descriptions generally omit design information (for example, type and thickness of cable insulation) and size (voltage or other size indicators). There is almost never any indication of the operating conditions or the level of maintenance. These omissions leave no guidance as to the weight that should be put on the data or its appropriate application.

Issues related to definition also abound. These include:

- Names for equipment. As an example data is provided for Switches, Substation disconnect switches, Overhead switches, Underground pad mount switches, Automatic transfer switches, Manual transfer switches, Oil filled switches, Switches >5kV and Static switches. The extent of overlap in these definitions and the similarities in the switches is unclear.
- What is a failure? Several sources distinguish between minor and major failures. Are only wear or age related failures reported? Are failures due to extreme weather conditions or accidents included? How are failures on parallel lines or closely associated pieces of equipment treated? Usually, sources do not answer these questions.
- What is included in time to repair? Does this include the time to locate, get crews to the problem, isolate, and repair or some subset of these activities? Again, sources usually do not answer these questions.
- Modeling terms such as hazard rate, failure function, extreme value distribution, Winfrey curve, and a number of others are often either poorly defined or, in some cases, obviously misused.

It should be noted that IEEE has recognized these definition problems for some time and has published several papers providing guidelines for definitions and the organization of databases of failure information. [IEEE, 1968], [Guertin, 1976] Utilities that follow these guidelines should have internally consistent data. However, the guidelines allow a good bit of flexibility and, even if utilities follow these recommendations, problems in combining information from different utilities are likely.

The discussions of data gathering, failure causes and maintenance make it very clear that identical equipment in different environments are likely to have very different failure rates and aging patterns. We might divide these factors into manufacture, environmental, use, and maintenance.

One manufacturing issue is design. We use cable as an example because it is perhaps the simplest piece of equipment. Cable obviously differs in size, but it also differs in the insulating material and its thickness. It differs in its protection; it can be direct buried, in jackets, in duct, or in conduit. It differs in the method of installation; it can be ploughed, buried in a trench, or placed in other manners. Damage during installation can cause different reliabilities. Cable differs in the depth of burial. Several studies show that even if all the design and installation specifications are the same, reliability can differ with manufacturer.

The reliability of outdoor equipment will depend significantly on weather. Temperature, humidity, wind, lightning, snow and ice are all significant. Location will affect risks from trees, animals, accidents and vandalism. Indoor equipment will be somewhat less affected, but temperature, moisture, and ventilation are still environmental issues.

The use of equipment also has an impact on its failure rate and aging. Probably the most obvious item is the impact of extreme loads on transformers, switches, and many other components. However, there are other obvious and less obvious factors. For equipment loaded intermittently, the hours of operation and the number of cycles are significant factors. One less obvious condition is the existence of harmonics and the problems they create. One paper noted that the speed of a switch can cause momentary overloads in the equipment it controls and thus contribute to the controlled equipment's reliability.

Maintenance is a final category that can significantly impact reliability. Almost all outdoor equipment requires some level of maintenance such as painting or other weather proofing. Lines require tree trimming and the removal of other hazards. Many more complex pieces of equipment require regular cleaning, fluid renewal, lubrication or other maintenance. Lack of such maintenance can significantly change reliability.

The final problem that we want to note is how to integrate monitoring into our repair, replace and maintain decisions. Many non-destructive, destructive, in situ and laboratory tests are available for components and are actively used by utilities. However, we have found very little information incorporating monitoring and testing results quantitatively into reliability estimates. This seems to be an area where rules of thumb and professional judgment rule.

By component

Buswork

While definitions are a problem throughout, they were an especial problem with respect to buswork. In a typical distribution substation design, on the low voltage side of the power transformer, there is metal-clad switchgear. This includes a drawout circuit breaker, feeder circuit breakers, busses, and various connections. It is unclear which specific components are included under terms found in the literature such as: bus, buswork, busbar, switchgear bus, and switchgear excluding circuit breakers. In this section, we assume these terms refer to similar components.

Data

Subcategories for buswork include: busbar; 132 kV busbars; switchgear bus, bare; switchgear bus, insulated; and bus duct, all types. For most of these items only one or two references were available for failure rates. For "switchgear bus, bare" four sources were available; however, failure rates ranged from 4.4E-04 units/year to 4.0E-02 units/year - nearly, a hundred fold difference. This wide range may be due to definitional problems or extremely varied uses for this category of equipment.

No data were found for the impact of aging.

Cable/Conductor

Data

Data for cables and conductors are listed under two major subheadings, overhead and underground, and under fifteen different minor subheadings. These are, for overhead conductors >15kV and <15kV and, for underground cables, approximately 600V solid, 15kV solid, 25kV solid, direct buried polyethylene (PE), direct buried HMWPE unjacketed, direct buried XLPE unjacketed, direct buried TRXLPE-SF-PEEJ, in duct XLPE, in cov. duct XLPE, in C.E. Duct XLPE, in C.E. duct TRXLPE-SF-PEEJ, 15kV paper, 25kV paper. Data on simple failure rates come from twelve different sources, and data on aging come from six different sources. We suspect that some of these sources are redundant in the sense that they draw from the same database of failures. (For example, the same author publishes similar data in two different papers.) However, we can't confirm the independence or dependence of sources.

Where we have three or more sources for the same titled item, simple failure rates typically differ by an order of magnitude. Here are some examples:

Table 3-3
Cable Failure Rates

Item	High	Low
Distribution	1.80E-00	1.22E-02
Aerial,<15kV	2.49E-01	1.22E-02
Underground	4.00E-01	1.17E-03
XLPE	4.02E-02	2.00E-03

With respect to aging, several sources show very little deterioration of cable with age. More typically the references show a doubling of failure rate from 10 year old cable to 30 year old cable. The most extreme is an approximate tripling of failure rate from 10 year old to 30 year old cable.

Causes

Overhead conductors fail due to overloading by snow or ice, tree problems, high winds causing clashing and arcing, and fatigue from vibration. Aluminum conductor may also be weakened by corrosion. [Wareing, 1998, p. 2/4-2/5]

In most areas, trees or branches falling, blowing, or growing into lines are the single greatest cause of outages. “$2 billion is spent on vegetation management each year.” [Willis, 2001(2), Section 7, p. 19] High winds and ice are often associated with tree problems.

In some areas, lightning may be the primary cause of overhead line failure. Lightning failures depend not only on the region and the level of thunderstorms, but the particular location of the line, such as an exposed hillside versus a valley, and the lightning protection from arrestors, insulators, use of overhead ground wires, level of grounding and soil moisture content.

Conductor is valuable and conductor theft can be a problem. [Wareing, 1998, p. 2/9]

Birds pose two problems: they bridge the conductors with their wings and with streaming excrement. [Willis, 2001(2), Section 7, p. 14]

Underground cable life is affected by voltage surges, through-faults, loading and environmental conditions such as temperature, moisture, and installation configuration.

Water treeing is a mode of ingress of water into solid cable insulation. It has been a significant problem. Recent tree-resistant insulations appear to be improving this problem. [Willis, 2001(2), Section 7. p. 5]

Dig-ins are the largest source of failure for underground cable. Apparently depth of burial has a significant impact on both dig-in failures and other failures. One source [Arceri, 1976, p. 37] shows that failure rates from all causes are reduced by 44% when burial depth is increased from 30 inches or less to 40-48 inches.

Tests

Visual inspections are commonly used for overhead lines. A visual inspection will identify loose components, improper grounding, missing notices, problem trees, and problem structures or activities

Tests for cable include: partial discharge testing, dielectric spectroscopy, degree of polymerization, and insulation hardness. [Willis, 2001(2), Section 7, p. 8] One source reports that a proprietary series of tests from Ultra Power Technologies, Inc. has proven extremely cost effective in identifying problem cable prior to failure. [Reder, 2000, p. 553]

Cable and Conductor Connections

Data

Data for splices is listed under 12 different headings. These are: pole top terminators, molded rubber; splices; 15kV solid splice; 25-kV solid splice; 15kV paper-solid splice; 25kV paper-solid splice; 25kV/15kV paper splice; elbows; loadbreak elbows/terminators; non-loadbreak elbows/terminators; 15-kV deadend cap. Data on simple failure rates come from ten different sources. Again, we suspect that some of these sources are redundant in the sense that they draw from the same database of failures.

There are three sources of data on aging.

Only one reference is available for pole top terminators. This shows a failure rate of 5.73E-05, a very low failure rate.

Underground splices have nine references. The failure rates for the general category splice range from 1.90E-04/year to 1.00E-03/year. However, a reference for the more specific category of 25kV solid-to-solid splices shows a high failure rate of 8.80E-01.

One source shows no deterioration of cable with age. Another source shows between a 2.5 and 3.0 multiple of the 10 year failure rate at 30 years.

Loadbreak elbows have a failure range from 2.63E-03 to 1.50E-03. Common references show consistently lower failure rates for non-loadbreak elbows. These range from 1.90E-04/year to 1.00E-03/year.

For underground splices, most references show failure rates rising by a factor of 3 to 3.5 from 10 years to 30 years of age. One reference shows the failure rate for loadbreak elbows rising by a factor of 4 from 10 years to 30 years of age. A second shows a rise over the same period of only about 75%. The single reference on aging in non-loadbreak elbows shows no deterioration with age.

Causes

Failures in overhead joints and accessories are often caused by improper design or installation. Stays can break due to fatigue or corrosion. [Wareing, 1998, p. 2/4] Wind can induce vibration which leads to fatigue. [Allison, 1995, p. 182]

Water has negative effects on both cable and cable joints. In particular in aluminum joints, water can react with the aluminum to create a gas, and the gas pressure can cause joints to fail.

Tests

Conductor corrosion can be detected by an eddy-current technique to detect the galvanic corrosion process in steel reinforced aluminum conductor. [Allison, 1995, p. 182]

Helicopter inspection of overhead lines can use a corona detection technique to identify fatigue fracture or wear in strands and fittings and an infra-red camera to detect joint deterioration. [Allison, 1995, p. 182]

Capacitor Banks

Data

There are five references for failure rates for capacitor banks. These range from 8.50E-03 up to 1.74E-01. The two references on aging in capacitor banks indicate that they age very significantly. One shows a five-fold and another shows a 35-fold increase in failures from 10 years to 30 years.

Causes

One study of capacitors indicated that the composite dielectric was the leading cause of failure. More fundamental problems are faulty seals, over voltage, and partial discharge. Oil switches create a particular problem. They produce a restrike after contacts have been opened, causing a switching overvoltage, which in turn causes a partial discharge, which in turn leads to degradation of the dielectric. [Faraq, 1999, p. 341-344]

Poles

Data

Only two sources were found for pole failure rates. The failure rates are very low. For wooden poles the given rates are 3.34E-05/year and 3.11E-04 at 10 years. For concrete poles, a 0.00E-00 is given at 10 years. At 30 years, the failure rate for wooden poles has risen significantly to 1.09E-03 and 2.04E-02, from the comparable references. For concrete poles at 30 years, the failure rate is more than 50 times lower than wood at 2.37E-05.

Causes

Steelwork faces rust problems, but steelwork is more generally replaced for re-conductoring with heavier conductor than due to failure [Wareing, 1998, p. 2/4].

Particularly in warm, moist environments rot is the main killer of wood poles. Drier climates cause pole checking which creates avenues for the entrance of wood destroyers. [Nelson, 1998, p. 3/3] Animals can also cause significant pole problems. Animals bridging phase wires can cause damage to pole tops. Wood peckers damage the structure of the poles. Burrowing can weaken soil support. Larger animals that use poles as rubbing posts can weaken poles. [Wareing, 1998, p. 2/9]

Tests

Visual inspection from the ground or from climbing/bucket trucks will look for loose components, improper grounding, out of plumb poles, missing notices, ineffective anti-climbing devices, ineffective stays and visible damage, such as from woodpeckers. [Nelson, 1998, p.3/4-3/5]

Other common tests for wood poles include: sounding, drilling or coring, and excavation. [Nelson, 1998, p. 3/5]

There are a number of more recently developed methods of decay detection.

- Sonic and ultrasonic devices send sound waves through the wood. Variations in speed indicate different wood densities; the speed is slower through less dense, weaker material. EPRI has developed a program that correlates results with the bending strength of poles.
- X-ray and NMR, nuclear magnetic resonance, devices also detect differences in densities. These technologies are more expensive than sonic devices but can create two- and three-dimensional mappings of pole densities.
- A decay detecting drill drills a very small whole with a flexible bit. It can detect differences in the hardness of the material being drilled through.
- Electrical resistance instruments operate on the principal that negative ions are released by wood when it is infected by decay.
- The *Polux* instrument has two electrodes that are driven into the wood. These electrodes measure density and moisture content. The density and moisture measurements have been correlated with compression strength as determined by destructive testing. The adequacy of pole strength is based upon the estimated compression strength.
- Mechanical deflection instruments apply a bending force in-situ and measure the deflection. [Nelson, 1998, p. 3/5-3/20]

Switches/Circuit Breakers/Fuses

Data

Data is available for eight headings under switches, eight headings under circuit breakers, reclosers, and three headings under fuses. These headings are: switches; substation disconnect switches; overhead switches; underground pad mount switches; automatic transfer; manual transfer; oil filled, >5kV; static; circuit breakers; < 600V; 11 kV; 63-100kV; 132 kV; circuit breaker 3 Phase, fixed; circuit breaker, drawout; circuit breaker, vacuum; recloser; fuses; overhead fuses; underground, fuses. For many of these headings, we have only one source. However, we have five sources for simple failure rates of substation disconnect switches, eight sources for overhead switches, and five sources for switches on underground systems. For the general category of circuit breakers, there are five sources. For reclosers, there are seven sources; and for fuses on overhead systems, there are eight sources. The table below lists lows and highs for these six components.

Table 3-4
Failure Rates of Switches, Circuit Breakers, Reclosers, and Fuses

	Failure Rate	
Component	**Low**	**High**
Substation Disconnect	1.50E-04	1.60E-01
Overhead	7.75E-04	1.40E-02
Underground	1.00E-03	1.00E-02
Circuit Breakers	3.00E-03	2.00E-02
Reclosers	1.44E-03	1.50E-02
Overhead Fuses	8.70E-04	4.5E-03

Where multiple sources are available, they suggest very different impacts of aging. One source shows no aging for switches from 10 to 30 years of age, another shows failures rising by a factor of five. Data for circuit breakers completely parallel that for switches, two sources show no impact of aging and a third shows failures rising by a factor of five. For reclosers and fuses, only one source is available for each. The recloser source shows a very low 25% increase in failures from 10 to 30 years. The fuses source shows no increase in failures over the same period.

Causes

Mechanical faults with the drive mechanism, contact erosion and leakage are the main problems experienced with circuit breakers. [Allison, 1995, p. 183]

Overloading and heat are the key underlying causes of switchgear failure. Heating problems can be exacerbated for outdoor equipment by solar radiation. Problem areas include:

- Contacts. Oxide film growth can lead to arcing at contacts. In air, this triggers insulation breakdown and flashover. In oil, this leads to gas generation and explosions.
- Compound insulation. Compound filled chambers leak with increasing operating temperatures, this can lead to busbar faults.
- PVC insulation. Overloads lead to cracking and ultimately to busbar faults. Overheating, particularly coupled with moisture, can reduce the insulation resistance of dielectric materials.
- Cable terminations. Expansion and contraction create severe mechanical forces that can lead to high resistance connections. Together with overloading this creates problems with insulation.
- Current transformers. Overloaded circuit breakers lead to overloads in associated current transformers. The temperature rating for the insulation on the secondary windings can be exceeded leading to shorted turns and protection failures. [Wareing, 1998, p.2/5]

A European study of circuit breakers of 63kV to over 700kV found that 43% of failures were in the operating mechanism and that 54% of failures could be attributed to design or manufacture. [Fletcher, 1995, p.28]

Corrosion is a major problem with switchgear used outdoors. If wind driven rain can enter joints and assemblies, corrosion problems are exacerbated. Visual inspection, cleaning, and painting are important maintenance items. [Pryor, 1987, p. 94] Bi-metallic corrosion has also been know to cause problems with contacts. [Pryor, 1987, p. 93]

Rodents and other small animals are a problem due to nesting in pad-mounted equipment.

Tests

Visual inspection can identify leakage in compound filled chambers. [Wareing, 1998, p. 2/6]. Visual inspection of gasketed joints for leakage and corrosion is also important.

Dielectric integrity is the only long-term factor associated with the deterioration of well maintained equipment. If switches are taken out of service, discharge testing can be performed in the laboratory. Bushings can be tested by capacitance, tan delta, and insulation resistance. Tests of insulating oil are also appropriate. [Pryor, 1987, p. 94-95]

Transformers

Data

The major classifications of transformers are substation, overhead or pole-mounted, pad-mounted, and submersible. In total, there are sixteen transformer headings under which we have data. These are: transformers, substation power transformers, 132/33kV transformer, overhead pole-mounted, 11kV/415V pole mounted, pad-mounted, 601v-15kV, 15kV, 25kV, 3 phase, 1 phase, forced air, submersible, vinyl, stainless, 1 phase below grade. For most of these categories, there are only one or two references. For pole-mounted and pad-mounted transformers there are eight sources for each.

Examining data from sources that cover several of the major transformer classifications, it suggests similar failure rates for pole-mounted, pad-mounted, and submersible transformers, and somewhat higher failure rates for substation power transformers. The table below shows the failure rate ranges for the major classes of transformers.

Table 3-5
Failure Rates for Transformers

	Failure Rates	
Component	**Low**	**High**
Substation	1.50E-02	7.00E-02
Pole-mounted	2.71E-04	5.00E-03
Pad-mounted	2.00E-03	4.73E-03
Submersible	1.38E-03	3.08E-03

There are two source for data on aging of pole-mounted transformers. The one we consider more reliable shows failures increasing by a factor of 50% from 10 years to 30 years. The other source shows a 15 fold increase in failures; however, this source also shows a 10 year failure rate $1/400^{th}$ of that from the other source. There are four sources for aging data on pad-mounted transformers. There is very little correspondence among these sources. According to the source, alternative rates of failure between 10 years and 30 years increase by 1) 6%, 2) 50% to 73%, 3) 2 to 5 fold, and 4) 125 fold. The single source of aging data for submersible transformers shows a 50% increase in failures from year 10 to 30.

Causes

A CIGRE survey indicated that windings and terminals were the leading components causing failure of transformers in service (29% of total failures each). A US survey indicated that external corrosion, aging, and insulating oil together accounted for 37% of the causes of transformer failure. [Allan, 1995(1), p. 67]

Because of the thickness of the transformer tank wall and the ease of detection of surface corrosion, corrosion is generally not a significant problem. Pole-mounted transformers are somewhat subject to rusting tanks and erosion of arc gap electrodes. Transformers with cooling radiators have more significant corrosion problems because rusting within the radiators is harder to detect. Submersible transformers have had particular rust problems, but these are much lower with more modern vinyl and stainless steel types [Verheiden, 1976, p. 18, 20].

Several environmental factors can lead to transformer damage. Lightning can induce faults, particularly in pole mounted transformers. Geomagnetic disturbances are a potential cause of failure. At times of high sunspot activity, an interaction occurs between charged particles thrown off by the sun and the earth's magnetic field. This interaction causes electric currents in the upper atmosphere and mirror currents in the earth's crust. When these currents take a path through the power system, the currents can saturate transformer cores, actuate protection systems and disconnect transformers. The saturation can cause overheating and the disconnections can overload adjacent lines. [Allan, 1995(1), p. 70]

For oil filled transformers, the aging rate of the insulation is determined by temperature and the moisture and oxygen content of the oil. [Ferguson, 1987, p. 116] Overloading that results in heating and insulation deterioration is a problem for all transformers. The temperature for normal aging is 98°C. In the rage of 80°C to 140°C for every 6°C deviation above or below 98°C doubles or halves the rate of aging respectively. [Wareing, 1998, p. 2/5] Another reference states that a 10°C deviation causes doubling. [Willis, 2001(2), Section 7, p.3]

Ferroresonance is a high voltage oscillation that can occur with overhead line phase switching. These oscillations can cause mechanical damage to transformers. [Wareing, 1998, p. 2/7]

Submersible transformers suffer failures of the elbow-bushing combination due to mechanical stress [Verheiden, 1976, p. 20]

Load tap changers have a history of failure; however, new vacuum technology is much improved. [Willis, 2001(2), Section 7, p. 3]

Load losses are much lower in new transformers than in old. These losses are another factor in the economics of transformer replacement. [Ferguson, 1987, p. 116]

Tests

Transformers can be inspected visually for rust and leakage. [Wareing, 1998, p. 2/5]

Condition of the insulating oil in transformers is of great concern. Tests include: dielectric breakdown, neutralization number, interfacial tension, specific gravity, water content, color, visual examination, power factor, flashpoint, pour point, corrosive sulfur, viscosity, dissolved gas analysis [ABB Power T&D Company, 2001, Section 4, p. 11-12] and furfaldehyde [Ferguson, 1987, p. 115].

Condition of the transformer winding insulation sets the ultimate transformer life. These are difficult to inspect directly. Some of the oil tests are directed at identifying winding insulation problems, such as the gas in oil test and furfaldehyde test. Electrical tests that can help diagnose problems include: insulation resistance by DC Megger, loss angle, partial discharge and low voltage impulse tests. [Ferguson, 1987, p.114]].

Windings can shrink with age and become loose within the transformer. Most transformers provide adjustable clamping to handle this problem. As an alternative to internal inspection for looseness there are electrical tests that can aid in detection. Two methods are to measure the reactance of the windings and to use a low voltage impulse. [Ferguson, 1987, p. 115]

Transformers have been extensively studied. Little information was found on the quantitative adjustment of failure rates based on the history of use and testing for other components; however, for transformers significant information was available. ABB provides some of these adjustment equations [ABB Power T&D Company, 2001, Section 3, p. 6-17]. ABB also provides the following list of minimum required information for calculating transformer life:

- Top oil temperature rise over ambient at rated load
- Bottom oil temperature rise over ambient at rated load
- Average conductor temperature rise over ambient at rated load
- Load loss at rated load
- No-load (Core) loss
- Total loss at rated load
- Confirmation of oil flow design (directed or non-directed)
- Core and coil assembly weight
- Tank and fitting weight
- Volume of oil in the tank and cooling equipment (excluding LTC compartments, oil expansion tanks, etc.) [ABB Power T&D Company, 2001, Section 3, p. 11]

ABB lists the following items as allowing more accurate prediction of transformer life:

- Load loss at rated and tap extremes or all possible tap connection combinations.
- Winding resistance at tap extremes or all possible tap combinations
- Total stay and eddy loss as a percent of total load loss and estimated stray and eddy loss.
- Per-unit winding height to hot-spot location
- Load cycle in kVA on the actual combination of tap connections
- Use the measured or calculated load losses for that tap connection
- Correct the temperature rise data for the lower losses or different rated current.
- Determine if the hottest-spot winding gradient changes with changes in the tap connections. [ABB Power T&D Company, 2001, Section 3, p. 11]

Observation and testing is also useful for ancillary transformer equipment such as bushings and load tap changers. Bushings should be checked for the state of their insulation and discharge characteristics. Oil filled bushings can be tested for gas in oil. Similarly, oil samples from the selector compartment of tap changers can be checked for gas in oil. [Ferguson, 1987, p. 115] Tap-changers are also subject to mechanical failure. Acoustic and optical sensors can monitor for tap-changer problems. [Allison, 1995, p. 183]

Others

Data

Many different types of components are included under the other category. These include: arrester, lightning, battery, inverters, all types, meter, electric, rectifiers, all types, secondary connectors, UPS, voltage regulator, static. Many of these items are used much more in industrial distribution systems than in utility distribution systems. Lightning arrestors and voltage regulators are perhaps the most important for utilities. Simple failure rates for lightning arrestors vary from 2.00E-04 to 1.32E-03 across four sources. Voltage regulators have five sources but we suspect several are redundant (same data source quoted by different papers). The simple failure rates for voltage regulators vary from 2.88E-02 to 3.63E-02.

There is one source of aging data for lightning arrestors. This shows the failure rate going up by a factor of about three from 10 years to 30 years.

Causes

Arrestors can deteriorate by leakage through end seals or gradual decay from use. Ferroresonance can cause ungapped metal oxide arrestors to fail due to long-term overloading.

4

CONCLUSIONS

While there is a great deal of information published about component failure rates, the failure rate information is inconsistent and there is limited data about the effects of aging. An examination of available information emphasizes the difficulty in interpreting published information and the wide range of failure rates that an individual utility might experience.

Three factors complicate the use of published data: data gathering and reporting, component variability, and the integration of monitoring data.

- Published data often is not accompanied by sufficient documentation to determine its accuracy or applicability to a particular utility and component. Terminology describing both components and failures is varied creating an additional communication problem.
- The failure rates of components can vary greatly with manufacturer and utility specific characteristics. These characteristics include design and manufacturing specifics, installation procedures, equipment operating environment, manner of equipment use, and maintenance procedures.
- Monitoring and testing can provide information on the condition of components, but interpretation of results is often qualitative. Seldom are quantitative relationships available between test results and failure rates.

Some of these problems would be alleviated by a larger collection of data gathered on many components in a consistent manner. We have not found a published source of such data in our search. There is a possibility that such data exists but has not been published. We have initiated contacts with several organizations that might hold such data. These organizations include: Edison Electric Institute (EEI); North American Electric Reliability Council (NERC); U.S. Army Corp of Engineers, Special Missions Office, Power Reliability Enhancement Program; Canadian Electricity Association (CEA); Electricity Association (EA, of England and Wales); International Council on Large Electric Systems (CIGRE); and ABB (global power and automation technology). As of publication of this report, these organizations have not responded, but we hope to establish communication with them in the future.

The results of this study should be of immediate use to utilities. The reference database should help planners locate information on: failure rates, causes of failures, and maintenance and monitoring procedures. The reference database also provides a guide to many case studies of failure rate analyses and approaches to system planning and design. Finally, the equipment database provides a quick source of failure rate data (this data should be used with an understanding of its limitations).

We believe that further research and data gathering can add significant value. We suggest that the following activities be undertaken:

- The reference and equipment summary databases should be maintained and expanded. If the databases become outdated, their current value will be lost. Given the foundation established by this report, maintenance and expansion should be significantly less costly than the initial development.
- We believe that individual utilities will use a combination of utility specific internal databases, published data, and expert judgment to develop databases that can be used for their system analyses. The specifics of what kind of database a utility needs and how these three sources can be used to establish such a database is unclear. Three to five published case studies could clarify this process and provide real and widely applicable examples of how a utility can quickly establish a useful database.
- Best practices for internal tracking of failure rates have not been established and widely disseminated. The data gathering process should be coordinated with the development of methods for analyzing aging systems currently ongoing at EPRI. This will assure the data and analytic procedures fit together. A guidebook on internal tracking of failure rates would document the best practices.

A
REFERENCES

ABB Power T&D Company.

ABB Power T&D Company, 2001

ABB Power T&D Company

"Equipment loading, lifetime replacement, and optimality workshop," 2001, February 23, EUCI, Denver, Colorado

A series of presentations at a workshop hosted by ABB Power T&D Co. Topics covered include conditions assessment, aging equipment and its impacts, aging power T&D infrastructures, transformer loading and loss of life determination, and planning for failures.

General overview of monitoring and testing. Lists diagnostic tests and provides a graph showing the relationship between Furanes and Degree of Polyermization of cellulose.

General overview of how failure rates are quantified, how maintenance and replacement affect overall failure rates, and how the population of units in service ages. Provides some failure rate data in the form of small graphs.

The section on aging power T&D infrastructures begins with a discussion of what aging or old equipment means and moves on to a very general discussion of managing aging equipment.

The transformer section provides a great deal of detail on how transformers age. It states that the normal life expectancy at 30 degree C and conductor hottest-spot temperature of 110 degree C is 20.55 years.

It includes discussions of the affects of aging, temperature, and loads. It provides equations to calculate insulation life in years based on hottest-spot temperature, ambient temperature, and loading. It, also, provides tables indicating impacts of ambient temperature and loading on life. It lists the following as necessary information to calculate loss of life: top oil temperature rise over ambient at rated load, bottom oil temperature rise over ambient at rated load, average conductor temperature rise over ambient at rated load, load loss at rated load, no-load (core) loss, total loss at rated load, confirmation of oil flow design (directed or non-directed), core and coil assembly weight, tank and fitting weight, volume of oil in the tank and cooling equipment (excluding LTC compartments, oil expansion tanks, etc.) It lists the following as useful information to calculate loss of life: Load loss at rated and tap extremes or all possible tap connection combinations, winding resistance at tap extremes or all possible tap combinations total stay and eddy loss as a percent of total load loss and estimated stray and eddy loss, and per-unit winding height to hot-spot location. The presentation also lists necessary adjustments needed to achieve more accurate capability predictions based on the actual load cycling and tap connections. The adjustments are based on load cycle in kVA on the actual combination of tap connections. The process is then to use the measured or calculated load losses for that tap connection, correct the temperature rise data for the lower losses or different rated current, and determine if the hottest-spot winding gradient changes with changes in the tap connections.

Any of the following may limit the loading to less than the capability of the winding insulation: Oil expansion, Pressure in sealed units, Thermal capability of bushings, Leads, Tap changers, Associated equipment - cables, reactors, circuit breakers, fuses, and disconnecting switches, current transformers. Also, operation at honest-spot temperatures above 140 °C may cause gassing in the solid insulation and the oil. Suggested limitations: Top Oil temp = 120 °C, Honest spot = 200 °C, Short-time loading = 300 % (1/2 hour or less).

The report provides a table of loss of life expectancy from short time loading with hot-spot temperatures above 110 °C.

The section on contingency and spares planning provides a conceptual overview of planning for contingencies and spares and monitoring. It also provides detailed lists of inspection, tests, and diagnostics for transformers, cables, and power systems.

Monitor power transformers for: Liquid level, Load current, Temperature, and Voltage. Perform the following inspections and tests on power transformers: Exterior for signs of damage & deterioration, Interior for signs of damage & deterioration, Check Ground connections, Lightning arresters, Protective devices and alarms, Radiators, pumps, valves and fans, Tap changer function, Other exterior ancillary devices.

Perform the following inspections and tests on power transformers solid insulation: Hi-pot (AC), Induced voltage, Insulation resistance, Power factor, Polarization index & recovery voltage, Perform the following inspections and tests on power transformers Insulating oil: Acidity, Color analysis, Dielectric strength, Interfacial tension, Power factor, TCGA, Perform the following inspections and tests on power transformers when condition is suspect: All inspections and above tests, TCGA (Gas chromatography), Insulation resistance, TTR

The following inspections and tests are suggested for cables (test and purpose are listed): Visual Inspection, Check for visible deterioration; leaks corrosion., Indentor Test, Track material deterioration; Insulation Resistance, Non-destructive test of insulation quality; PD Test, Detect flaws/incipient failures, High stress; Hi-potential (DC), Detect flaws/incipient failures, Very high stress; and Fault location, Identify failure location.

The following additional inspection and tests are suggested for the power system: Thermal load, Resistance, Dielectric, Absorption, Power Factor, Polarization recovery., Hi-pot, Induced, Partial, Discharge, Transformer Turns Ratio, Oil acidity, Interfacial, TCGA, DGA, Disassembly/ Inspection.

On page 4 of the Aging Equipment and Its Impacts section there are three small graphs showing failure rates. No information is provided on sample size or time period for collection. Graph 1 shows failures per year versus age in years for 25-kV solid, 15-kV solid, 25-kV paper, and 15-

kV paper cable sections. Graph 2 shows failures per year versus age in years for 25-kV solid, 15-kV solid, 25-kV paper, 15-kV paper, 25-kV solid-paper, 15-kV solid-paper cable joints. Graph 3 shows failures per year versus age in years for 25-kV and 15-kV pad-mounted transformers.

On page 12 of the Aging Equipment and Its Impacts section the graph regarding pad-mounted transformers in shown in larger scale.

On page 6 of the Transformer Loading and Loss of Life Determination section there is a equation for the per unit insulation life with specified parameters. Independent variable is the winding hottest-spot temperature.

On page 7 of the Transformer Loading and Loss of Life Determination section there is a equation for the Aging Acceleration Factor or Faa and Feqa the equivalent life consumed in given time period for a given temperature cycle with specified parameters Faa and Feqa are used to calculate the equivalent age and percent loss of total life of a transformer. The independent variables are the winding hottest-spot temperatures and duration at each temperature.

On page 8 of the Transformer Loading and Loss of Life Determination section there is a equation for the percent loss of total life with specified parameters. The independent variables are Feqa, the normal insulation life, and the age of the transformer.

On page 10 of the Transformer Loading and Loss of Life Determination section there is a Table describing the of ambient temperature on loading and aging. Rows of the table indicate the type of cooling, The first column is the decrease in loading as a percent of kVa rating needed to preserve normal life expectancy for each one degree C increase in ambient temperature. The second column is the increase in loading as a percent of kVa rating allowed to preserve normal life expectancy for each one degree C decrease in ambient temperature.

On page 14 of the Transformer Loading and Loss of Life Determination section there is a Table describing the loss of life expectancy from short periods of loading at higher than normal hottest-spot temperatures. Columns are times, rows are % loss of life, and entries are temperatures.

On page 17 of the Transformer Loading and Loss of Life Determination section there is a Table describing limits on loading stated as temperatures. Rows of the table refer to insulated conductor hottest-spot temperature, other metallic hot-spot temperature, and top oil temperature. Columns refer to normal life expectancy loading, panned loading beyond name plate, long-time emergency loading, short-time emergency loading.

The following references may be of interest. H.L. Willis, Power Distribution Planning Reference Book, Marcel Dekker, Inc., 1997; H.L. Willis, Aging Power Delivery Infrastructures, Marcel Dekker, Inc., 2001; Paul Gill, Electrical Power Equipment Maintenance and Testing, Marcel Dekker, Inc., 1998

Search terms and ID: Multiple, Data, Equations, Presentation, 62

Alexander, 1994

Alexander, Harold; Rogge, Dan

"Harmonics: causes, problems, solutions.(part 2)," EC&M Electrical Construction & Maintenance, 1994, February, Intertec

Discusses the problems caused by harmonics and presents some approaches to reducing harmonics. Has an extensive reference list. The article does not discuss the relationship of harmonics to aging, nor is there any discussion of economic consequences of harmonics.

Harmonics can cause:

- Overheating in transformers
- Problems with power factor
- Blown fuses and disfigured capacitors
- Fuses overheat and have nuisance tripping
- Problems with inverse time circuit breakers
- Problems with protective relays

Search terms and ID: Multiple, Causes, Design, Journal Article, 55

Allan, 1995(1)

Allan, D.J.; White, A.

"Transformer Design for High Reliability," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 66-72, IEE, Norwich, UK

Design of transformers is being increasingly guided by cost of ownership. This paper discusses how manufacturers are increasing dependability and reliability to reduce the cost of ownership.

Paper focuses on design topics, but there is ample data regarding transformer failures. Table 1 displays the main causes of failure to transformers in service (CIGRE survey). Table 2 displays a list of components causing failure in service (CIGRE survey)

Search terms and ID: Transformers, Design, Causes, Proceedings, 68

Allan, 1995(2)

Allan, R.N.; Billinton, R.

"Concepts of Data for Assessing the Reliability of Transmission and Distribution Equipment," Reliability of Transmission and Distribution Equipment, The, 1995, 29-Mar, 406, 6-Jan, IEE, Norwich, UK

Paper discusses the concept of data and the data necessary for analysis, modelling and predictive assessments. Data can be used for assessment of past performance and/or prediction of future performance. Failure processes, such as short circuit failures, open circuit failures, switching failures and environmental failures, are also discussed.

General discussion of data. No actual data is presented.

Search terms and ID: System, Data, Causes, Journal Article, 83

Allan, 1983(1)

Allan, R.N.; Avouris, N.M.; Kozlowski, A.; Williams, G.T.

"Common Mode Failure Analysis in the Reliability Evaluation of Electrical Auxiliary Systems," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 132-136, IEE, London, United Kingdom

This paper discusses four types of failures that have been simulated to assess the reliability of electrical auxiliary systems. The models incorporate the effect of common failures of auxiliary systems, and the paper concludes that in one of the models presented that common mode failures had a considerable effect on busbar unavailability.

This paper mostly discusses mathematical equations for failure sequences. Data is provided for a sample system, but the data appears to be hypothetical and system components are not well identified.

Search terms and ID: System, Technical, Proceedings, 8

Allan, 1983(2)

Allan, R.N.; De Oliveira, M.F. ; Chambers, U.A.; Billinton, R.

"Reliability Effects of the Electrical Auxiliary Systems in Power Stations," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 28-31, IEE, London, United Kingdom

Provides calculations for comparing alternative designs, quantify reliability, and identify possible failure modes. Calculations are based upon incorporating realistic failure modes and restoration procedures involving main, guaranteed and essential systems. Alternative designs that meet reliability criteria can than be compared on a cost to benefits basis.

Table 1 provides the following data: Total Failure Rate, f/yr; Active Failure Rate, f/yr; Repair Time; Stuck Probability; Maintenance Time; Maintenance Rate; and Switching time (columns). The components in rows are designated in a circuit diagram. The source of the data is not provided. This article mostly discusses busbar reliability and provides a table of busbar reliability.

Search terms and ID: System, Technical, Data, Journal Article, 11

Allan, 1983(3)

Allan, R.N.; De Oliveira, M.F.

"Reliability Analysis in the Design of Transmission and Distribution Systems," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 58-61, IEE, London

This paper discusses restoration models that follow point load failures that can be identified from component outage modes for distribution and transmission systems. Multiple approaches for evaluating reliability are presented and their individual merits discussed.

The source of the reliability data is not referenced. Table 2 presents reliability data for busbars, breakers, transformers, and lines (rows). Data presented (columns) includes: total failures/year, active failures/year, temporary failures/year, maintenance outages per year, repair time, switching time, reclosure time, maintenance time, stuck probability.

Search terms and ID: Multiple, Technical, Proceedings, 12

Allen, 1995

Allen, J.N.

“System Reliability Improvement--An Australian Experience,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 139-144, IEE, Norwich, United Kingdom

Description of implementation of strategies to improve system performance and improved service to an Australian utility. Total Quality Management and Quality Task Teams are discussed.

Figures present the causes and effects of failure for 11 kV feeder faults. Other figures display a historic reliability index, a "fishbone" diagram of failure root causes of 11 kV feeder faults. Further figures provide data regarding lost energy sales, causes of failures, failed components, and historic reliability. The measure for historic reliability is minute/customer/annum.

Search terms and ID: System, Design, Data, Proceedings, 71

Allison, 1995

Allison, M.R.; Lewis, K.G.; Winfield, M.L.

“Integrated Approach To Reliability Assessment, Maintenance and Life Cycle Costs in the National Grid Company, An,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 180-185, IEE, Norwich, UK

Discussion of maintenance and asset replacement strategies and techniques based on the behavior and performance of the equipment involved. Maintenance policies, asset replacement and transmission system reliability are discussed.

Figure 1 displays failure rate percentages per year (1982 through 1993) for 400 kV circuit breakers. Data regarding plant equipment installation dates and other qualitative data is presented.

Search terms and ID: Multiple, Maintenance, Data, Proceedings, 75

Arceri, 1976

Arceri, John A.

"Statistical Analysis and Review of Underground Distribution Systems and Equipment," IEEE Conference Record - Supplement 1976 Underground Transmission and Distribution Conference, 76 CH1119-7-PWR (SUP), 1976, Sept. 27-Oct. 1, 34-38, IEEE

Paper displays underground distribution system and equipment data from 38 major utilities.

Background data is presented regarding the utilities represented by the data and expected failures/100 miles/year due to dig-ins. Figures 8 and 9 display graphs of average new installations per year per utility as a function of time (years). Figure 10 displays failure rates for direct buried primary cables. Figure 11 is similar to Figure 10, but failure rates are presented as a function of cable depth. Figure 12 displays annual failure rate per year for primary molded elbows. Figure 13 displays annual failure rate per year for primary molded splices. Figure 14 displays annual failure rate per year for pad-mounted and below grade single phase transformers. Figure 15 displays annual failure rate per year for pad-mounted three phase transformers. Figure 16 summarizes the data from the article in terms of failure rates of underground equipment and overhead equipment.

Search terms and ID: System, Data, Causes, Journal Article, 101

Atkinson, 1987

Atkinson, W.C.; Ellis, F.E.

"Electricity distribution asset-replacement considerations," Electronics & Power, 1987, May

The paper describes the age distribution of key distribution assets in the power system of England and Wales. It notes that age alone does not determine the need for replacement. Factors such as: original design, materials used, environment, loading, maintenance, technology, and suitability for refurbishing affect the need for replacement. Discusses issues such a monitoring, technology change, typical installations, and other issues surrounding each type of equipment.

Search terms and ID: Multiple, Monitoring, Maintenance, Journal Article, 222

Barber, 1995

Barber, Fred; Hilberg, Gary

"Comprehensive maintenance program ensures reliable operation," Power engineering, 1995, December, 99, 12, 27

Provides some background on common preventative maintenance (PM) practices at Independent Power Producers' (IPP's) generators. Describes the PM program at North American Energy Services in some detail. Notes that most IPP's use computerized maintenance systems.

Search terms and ID: Generators, Maintenance, Journal Article, 206

Bargigia, 1991

Bargigia, A ; Heising, C.R.

“High Voltage Circuit Breaker Reliability Data For Use In System Reliability Studies,” CIGRE Symposium on Electric Power System Reliability, Montreal 1991, 1991, September 16-18, 1-6, CIGRE

"This articles summarizes two international studies on high-voltage circuit breakers. First, there are data on 20000 miscellaneous breakers from 1974-1977, an effort that involved 102 utilities in 22 countries. Second is data on 16500 of the newer technology single-pressure SF6 breakers from 1988-1989, which is the first half of a 4-year study involving 100 utilities in 18 countries. It presents raw data failure rates for a number of failure modes and calculated probability results that can be used in system reliability studies. The Working Group includes definitions of the different events. The possible failure modes include not responding to an operating command. The combination of the results from the two studies covers both older technology circuit breakers and the newer SF6 circuit breakers for system reliability studies.

Discussion of data collected from two studies regarding circuit breakers. World-wide reliability data was collected for 63 kV and above circuit breakers in greater detail than typical for system reliability studies. Reliability was based on the following failure types: 1) Failure; 2) Major Failure; 3) Minor Failure; 4) Defect; and 5) Circuit Breaker Downtime."

Table 2 - Failure rates and downtime data for high voltage circuit breakers above 63 kV. Rows: All voltages, 63<V<100, 100<V<200,200<V<300, 300<V<500, 500<V. Columns: Major failures sample size-breaker years, Number of major failures, Major failures per breaker year, Major failures Hours downtime per failure average and median, Minor failures sample size-breaker years, Number of minor failures, minor failures per breaker year.

Table 3 - Major failure modes of high voltage circuit breakers. Rows are failure modes. Columns are breaker sizes. Entries are percentage of failures.

Table 4 - Estimated average number of operating-cycles per year per breaker. Rows are percentiles. Columns are breaker sizes. Entries are number of operating-cycles per year per breaker.

Table 5 - Reliability data on high-voltage circuit breakers above 63 kV that can be used in system reliability studies. Entries are failure rates. Rows are breaker sizes. Columns are: Does not open on command, does not break the current, does not close on command, does not make

the current, major failures per operating cycle, average number o operating cycles per year, major failure per breaker year during command, major failure per breaker year without a command, Total major failure per breaker year.

Table 6 - Failure rates and downtime data for single-pressure high-voltage circuit breakers above 63 kV. Rows: All voltages, 63<V<100, 100<V<200,200<V<300, 300<V<500, 500<V. Columns: Sample size-breaker years, Number of major failures, Major failures per breaker year, Major failures Hours downtime per failure average and median, Number of minor failures, minor failures per breaker year.

Table 7 - Major failure modes of single-pressure high-voltage circuit breakers. Rows are failure modes. Columns are breaker sizes. Entries are percentage of failures.

Table 8 - Estimated average number of operating-cycles per year per single-pressure breaker. Rows are percentiles. Columns are breaker sizes. Entries are number of operating-cycles per year per breaker.

Table 9-Table 5 - Reliability data on single-pressure high-voltage circuit breakers above 63 kV that can be used in system reliability studies. Table structure identical to Table 5.

Table 10 - Same as Table 9, except that Major Failures per Operating Cycle could be increased by with the assumption that each locking in open or closed position failure resulted from one command to open or close."

Search terms and ID: Switches, Data, Journal Article, 49

Basille, 1995

Basille, C.; Aupied, J.; Sanshis, G.

“Application of RCM to High Voltage Substations,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 186-191, IEE, Norwich, United Kingdom

Reliability Centered Maintenance (RCM) adopts probabilistic and Bayesian techniques to take criticality into account. Efficiency, cost, and operational discomfort are taken into account in improvements based on reliability. Various system personnel are able to combine knowledge in this framework.

Pilot study conducted on a 400 kV line bay. Task selection, decision principles and influence of maintenance on failures are expressed in diagrams. No quantitative data is presented.

Search terms and ID: System, Technical, Proceedings, 76

Baxter, 1988

Baxter, M.J.; Bendell, A. ; Manning, P.T.; Ryan, S.G.

“Proportional hazards modeling of transmission equipment failures,” Reliability engineering and system safety, 1988, 21, 129-144, Elsevier, Great Britain

"The paper applies Proportional Hazard Modeling (PHM) to two subsets of the Central Electricity Generating Board (CEGB), UK, transmission failure and repair database and investigates the influence of external variables on the failure and repair data. Proportional hazards modeling (PHM) is a technique for ensuring that assumptions used in reliability models are compatible with the data structure. The objectives of the paper may be summarized as: to ascertain the relevance of PHM towards the analysis of the transmission reliability data, to compare and contrast the results for disparate geographical areas, and to determine the validity of the reliability models in current use.

The paper starts by introducing PHM, which describes the relation between hazard rate and a set of external variables, as the exponential of a linear combination of the external variables multiplied by a base-line hazard function (hazard rate is a function of time whose integral within a given interval gives expected number of failures in that interval). The authors attempt to provide a way to test the effect of additional variables, such as weather, on the hazard rate. Base-line hazard function is equivalent to hazard rate function if all external variables are equal to zero and the rest of the paper deals with a distribution free approach where the base-line hazard function is non-parametrically estimated from data.

The authors introduce the application section with a word of caution that PHM, just as any other reliability analysis technique, not be used as an automatic black-box method but rather in an exploratory mode, with repeated applications of varying formulations in order to identify and focus explanatory power on the failure processes involved. The authors conclude that the ability to investigate all potential variables (provided by PHM exploratory advantage) for which either a proper numerical or classification is available in the data is a major advantage, rather than having to rely, as in more traditional reliability analysis, on implicit assumptions of homogeneity. In the particular context of CEGB transmission systems, the method has confirmed its relevance and power providing results of similar causal structure, and parameter estimates of similar size, in disparate geographical areas.

Data is from the transmission system of the Central Electricity Generating Board (CEGB) in England and Wales. Data on faults for this system has been collected since 1996 however the precise period for this data is not presented. There was also no information on the number of components covered by the data. Table 2 presents data on lines, circuit breakers, protection equipment, transformers, and isolators (Rows). Columns are total number of faults and potential causes. Causes include weather, season, environmental (cause), and voltage. Entries are counts. A total of 1747 faults are considered.

In two other tables time between faults and restoration times are considered for the same equipment.

Overhead line failures had greatest impact on system reliability. Weather, season, and time are significant. The pattern of failure is not random, but they occur in "bunches" linked to adverse environmental conditions (chances of faults due to environmental conditions are 1000 times higher than under normal conditions).

The covarients presented in the article are weather, season, cause, voltage and time.

For PHM to be worthwhile, there needs to be a lot of data. The technique worked well for overhead lines in this article because there was plenty of relevant data.

A lot of data is presented, but it is all in the context of PHM models."

Search terms and ID: Multiple, Technical, Data, Journal Article, 59

Beaty, 1997

Beaty, Wayne

"Transmission systems struggle to keep pace with growth," Electric light & power, 1997, May, 75, 5, 18

Wide ranging discussion of the current status of U.S. transmission systems. Covers difficulty of line construction, technical solutions for transmission reliability problems, and maintenance.

Search terms and ID: System, Design, Maintenance, Journal Article, 209

Beaty, 1995

Beaty, Wayne

"Maintenance is key to competitiveness and reliability," Electric light & power, 1995, June, 73, 6, 32

Discusses several trends in monitoring and maintenance of distribution systems. These include: the use of inspection services, robotics, and vegetation management.

Search terms and ID: System, Monitoring, Maintenance, Journal Article, 212

Begian, 1972

Begian, Sam S.

“Data Collection System for Analyzing Transmission and Distribution Performance,” 1972, 1-4, IEEE

Paper describes a method to gather, distribute and analyze outage data.

Qualitative description of a data collection system. No data is presented.

Search terms and ID: System, Data, Causes, Journal Article, 103

Berg, 1997

Berg, Menachem

“Performance Comparisons for Maintained Items,” Mathematical Methods of Operations Research, 1997, 45, 377-385, Physica-Verlag, Heidelberg, Germany

Focus of the paper is on the improvement in performance that results from a maintenance action. Different modeling situations are considered, and for each of them conditions are obtained on the life distribution of the present item and the new one if of different type, that ensure performance improvement. The paper also deals extensively with probabilistic ordering notions and aging properties. The paper is theoretical and does not provide numerical examples.

High level theoretical paper. No indications of applications.

Search terms and ID: Non-specific, Financial, Technical, Journal Article, 201

Berg, 1995

Berg, Menachem

“Age-Dependent Failure Modeling: A Hazard-Function Approach,” 9569, 1995, June, Center for Economic Research

Paper presents a mathematical tool for age-dependent failure modeling that separates assets into two categories: those discarded upon first failure and those that are repaired. For those assets discarded after first failure, the hazard function is a function of failure mechanism and life distribution. There can only be one failure mechanism, which is dependent on age. The author discusses mathematical functions that describe failure mechanisms and that the reliability of such mechanisms is dependent on goodness of fit, flexibility, and lack of sufficient data. For repairable systems, the author states that age is not the only necessary data.

The paper includes discussions of hazard rate ordering. Aging characteristics belong in the realm of the single-fault case since they depend only upon the age of the asset. Modeling of age-dependent failure mechanisms is better when hazard functions are used.

Search terms and ID: Multiple, Technical, Report, 21

Billinton, 1995

Billinton, R.; Ghajar, G.; Filippelli, F.; Del Bianco, R.

"Transmission Equipment Reliability Using the Canadian Electrical Association Information System," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 13-18, IEE, Norwich, United Kingdom

Canadian data from 1988 to 1992 regarding the reliability of power distribution components, with data subdivided into voltage categories.

"Data is from the period 1/1/1988 to 12/31, 1992, Canadian Electrical Association Equipment Reliability Information System (CEA-ERIS). Data is for 110kV to 799kV divided into 6 classes by size. Tables for transmission lines and cables (Tables 1 and 2) provide outage frequency, mean duration and percent unavailable data. Tables for transformers, circuit breakers, synchronous compensators, shunt reactors, shunt capacitors, and series capacitors (Tables 3, 4,5, 6,7, 8, and9) provide frequency and mean duration.

We have a copy of the full report for the 1/1/1992 to 12/31/1996 period. "

Search terms and ID: Multiple, Data, Proceedings, 64

Billinton, 1993

Billinton, R.; Gupta, R. ; Chowdhury, N.A.; Goel, L.

"Computer Programs for Reliability Evaluation of Distribution Systems," International Power Engineering Conference 1993, 1993, March 18, 37-42

Paper presents computer programs that help perform reliability assessments for subtransmission and radial distribution configurations. The programs allow for faster computation and sensitivity analyses in systems with increasing components. Some sample data for components is presented.

The calculations are performed on a reliability test system designated as the RBTS. No data sources are specified other than this system. References for the system are listed. The reliability data is found in Table 4. Components (rows) are Transformer, breakers, busbars, and lines.

Failure data (columns) include: Permanent failure rate, Active failure rate, Temp. failure rate, maintenance outage rate, Repair time, Maintenance time, Reclosure time, Switching time.

Search terms and ID: Multiple, Technical, Data, Proceedings, 52

Billinton, 1987

Billinton, C.J.; Billinton, J.E.; Billinton, R.

"Service Continuity Performance of Canadian Electric Power Utilities - A Historical Perspective," Proceedings of the 14th Inter-RAM Conference for the Electric Power Industry, Toronto, Canada, May 1987., 1987, May, 456-463

Canadian electric power utilities have collected service continuity statistics for over twenty years. These statistics show that the participating utilities 'have an excellent record of service continuity performance. The collection procedure has undergone many changes since It was initiated in 1961 and has now evolved into a useful and important indicator of both individual utility and national service continuity performance. This paper traces the evolution of this system and the participation of Canadian utilities. The contribution to the service continuity statistics of such factors as loss of supply, adverse weather and defective equipment is illustrated.

The paper presents interesting statistics on index of reliability and SAIFI overtime and for individual utilities. It also presents interesting data regarding the causes of customer outages. However, it presents no component level data.

Search terms and ID: System, Data, Proceedings, 259

Billinton, 1978(1)

Billinton, Roy

"Transmission System Reliability Models," Workshop Proceedings: Power System Reliability--Research Needs and Priorities, WS-77-60, 1978, March 5-9, 2-10 through 2-17, EPRI

Author begins by describing the need for, and absence of, adequate transmission system reliability models. A basic model for common cause failures is presented and discussed. A discussion of the need for realistic common-cause models is also included.

Some failure probability data is presented for hypothetical models. Paper presents little in terms of aging asset failure data or models.

Search terms and ID: Non-specific, Model, Data, Report, 114

Billinton, 1978(1)

Billinton, R.; Medicherla, T. K. P.; Sachdev, M. S.

"Common Cause Outages in Multiple Circuit Transmission Lines," IEEE Transactions on Reliability, 1978, June, R-2, 5, 128-131, IEEE

Reliability evaluation of a power system involving both generation and transmission elements is extremely complex. Outages of these elements are usually considered to be s-independent events. Recent investigations, however, have indicated that common-cause outages of multicircuit transmission configurations can appreciably affect the predicted reliability. Closed form expressions for steady state probabilities in 2- and 3-line cases (including certain common-cause failures) are developed. These expressions provide transmission-line state probabilities for composite generation and transmission system reliability studies. The procedure can also be used to develop state probabilities for other line models and for systems with four or more lines on the same right-of-way. The examples show the influence of the common-cause outage rate on the state probabilities. There is a definite need to include common-cause outages in reliability evaluation of transmission systems. This will require a more comprehensive approach to collecting transmission line outage data than has previously been used by most utilities.

Table 1 reports outages/100 miles-year and repair duration in hours for 69, 138, 161, 345, and 500 kV lines. The data is based on the summer line outage experience of Oklahoma Gas and Electric Company. Lightning outages are uncommon in Oklahoma during the summer and therefore the outage rates do not include outages due to lightning. No other information is presented on the outage data.

Search terms and ID: System, Technical, Data, Journal Article, 248

Billinton, 1976

Billinton, Roy; Crousse, John H. T.; Miller, W. T. ; Pontifex, C. E.; Troalen, P. ; Wicentovich, M. N.

"Distribution System Reliability Engineering Guide," 1976, March, 105, Canadian Electricity Association

The reliability engineering guide provided by the CEA has the fundamental series-parallel reduction modeling information that has been in place for over 25 years. It states that there existed at the time of writing a suitable methodology for predicting reliability indices, but component outage data has lagged behind. The initial reliability indices defined were customer-hours of interruption and kVA-hours of interruption, before frequency and duration. The indices defined here are SAIFI, CAIFI, SAIDI, CAIDI, ALII, ASCI, and ACCI, as contained in an early IEEE standard (# 346-1973). The guide discusses reliability criteria based on outage frequency, average duration, and expected annual outage time can be used to assess continuity. The appendices illustrate a number of calculation examples for predictive reliability assessment of small portions of systems, including one example comparing 2 alternatives considering reliability worth.

The report provides very little data. The data provided is to illustrate example calculations. References for the data are generally not provided.

On page 19, a table of Maximum Actual Restoration Time is provided. The data is from the period 1969 to 1973. Columns of the table indicate component involved, time when personnel on duty, time when sectionalizing available, all other cases. Rows cover Substations of different sizes, Substation bus sections, and circuits.

Page 39 there is illustrative failure data for a manually sectionalized primary main.

Page 44 there is illustrative failure data for a 46-kV substation.

Page 47 there is illustrative failure data for a distribution substation.

Page 49 there is illustrative failure data for a subtransmission system."

Search terms and ID: System, Technical, Data, Report, 218

Blaicher, 1975

Blaicher, Herbert E.

"Open Forum: Equipment Failure Reporting Systems," Undergrounding, 1975, January/February

Article presents interviews with four industry practitioners regarding their efforts in implementing failure reporting systems.

No data is presented.

Search terms and ID: Non-specific, Other, Journal Article, 124

Brint, 2000

Brint, A.T.

"Sequential inspection sampling to avoid failure critical items being in an at risk condition," Journal of the Operational Research Society, 2000, Sept, 51, 9, 1051-1059, Stockton Press for the Oper. Res. Soc, The problem of how to extend the time interval of fixed time period maintenance for items whose failure can be catastrophic, is considered. The paper proposes a coherent methodology particularly applicable to switchgear used within electricity distribution networks. The methodology involves taking a sample of the items and based on their observed conditions, deciding whether to: maintain, defer maintenance, or take another sample. Consideration of the precise problem to be solved leads to a Bayesian formulation. The predictive distribution is then used to determine the expected outcome of taking further observations. Results using simulated and real data are reported. This sequential sampling approach seems particularly appropriate for distribution networks where inspection costs can be relatively high.

The real data reported is the moisture level within switches. An arbitrary maximum moisture level is defined.

Search terms and ID: Switches, Technical, Journal Article, 239

Brown, 2001

Brown, R.E.

"Probabilistic reliability and risk assessment of electric power distribution systems," Distributech 2001, 2001

To provide high levels of customer reliability for the lowest possible cost, utilities must plan and engineer the reliability of distribution systems. Just as capacity engineering requires tools to predict currents and voltages based on loading data, reliability engineering requires tools capable of predicting interruption characteristics based on component reliability data. This paper presents an analytical simulation that can represent detailed reliability characteristics, is computationally efficient and is suitable for computing expected values related to momentary interruptions and sustained interruptions. The analytical simulation is then extended into a hybrid analytical/Monte Carlo simulation that is more computationally intensive, but is capable of producing a probability distribution of annual reliability behavior that is suitable for risk analyses. Characteristics and capabilities of these two methodologies are demonstrated on a distribution system subject to performance based rates.

No data is reported on specific equipment.

Search terms and ID: System, Financial, Proceedings, 265

Brown, 2000(1)

Brown, R.E.; Howe, B.

“Optimal deployment of reliability investments,” The Power Quality Series, 2000, April, PQ-6, E source

Describes the current distribution system planning environment, utility and customer financial impacts of poor reliability, traditional approaches to estimating system reliability indices such as SAIDI, analytic approaches to calculating the value of system upgrades or optimizing system designs, and case studies of projects to upgrade system reliability. The report argues that performance based regulation, liability to customers for losses due to outages, and other factors are increasing the importance of distribution system reliability. The report argues that utilities need to examine utility and customer costs and evaluate distribution system maintenance and replacement projects based on the minimization of these costs. The next section discusses specific technical approaches to estimating system reliability and costs. The final two sections present two case studies: the first looks at five alternatives for improving the reliability of the distribution system for an oil refinery and the second looks at alternative to improving reliability in a neighborhood in a quickly developing urban area.

No data is reported on specific equipment.

Search terms and ID: System, Financial, Other, Report, 262

Brown, 2000(2)

Brown, R.E.

“Impact of heuristic initialization on distribution system reliability optimization, The,” Engineering Intelligent Systems, 2000, March, 8, 1, 29-36, CRL Publishing

Deregulation of the electricity market is, ironically, resulting in more regulation on distribution systems. Regulators, fearful that cost cutting will result in reduced reliability, are using performance-based rates to penalize utilities if reliability deteriorates. A distribution system subject to performance-based rates has an optimal configuration that best balances equipment cost and reliability penalties. This paper develops and compares several algorithms capable of optimizing distributions systems in this context. The basic form of each algorithm (integer programming, simulated annealing, and genetic algorithms) uses random solutions for initialization. This paper examines the impact of replacing random initialization with initialization based on heuristic knowledge encoded into fuzzy rules. Genetic algorithms with heuristic initialization are shown to outperform other optimization methods.

This is a highly technical paper focused on the performance of specific mathematical optimization techniques in estimating the reliability of different distribution system designs. Table 3 provides the failure information for a test system used to compare the optimization techniques. Data is provided (in rows) for overhead lines, underground cables, reclosers, fuses, manual switch, and automated switch. The data (in columns) include failure rates, mean time to repair, mean time to switch, and probability of operational failure.

Search terms and ID: Multiple, Financial, Data, Journal, 263

Brown, 1998

Brown, R.E.; Ocha, J.R.

"Distribution System Reliability: Default Data and Model Validation," IEEE Transactions on Power Systems, 1998, May, 13, 2, 704-708, IEEE

A method for determining appropriate component reliability values is presented that matches predicted indices to historical indices. This is necessary because most utilities do not have sufficient historical data to adequately represent their system in a reliability analysis. This validation method presents a way of gaining confidence in a reliability model. The method is applied to parameters such as MAIFI, SAIFI, SAIDI, etc.

Initial failure rate data come from the RBTS, test system developed by R. Allan, R. Billinton, I Sjarief, L. Goel, and K. So. (See "A Reliability Test System for Educational Purposes-Basic Distribution System Data and Results, " IEEE Transaction on Power Systems, Vol.6, No. 2, May 1991, pp. 813-820 by the listed authors.) Table 1 provides data for feeders, reclosers, fuses, switches, STS (rows). Data provided are Sustained failure rate, Momentary failure rate, Mean time to repair, Probability of successful switching (columns). Case studies are presented. Line failure rates are a function of vegetation, tree trimming, weather, etc., so previously published representative data is difficult to apply to other systems. MAIFI an SAIFI are predominantly affected by overhead lines.

Search terms and ID: Multiple, Technical, Data, Journal Article, 43

Bucci, 1994

Bucci, R.M.; Rebbaragada, R. V.; McElroy, A. J.; Chebli, E. A.; Driller, S.

"Failure Prediction of Underground Distribution Feeder Cables," IEEE Transactions on Power Delivery, 1994, October, 9, 4, 1943-1955, IEEE

This paper presents a methodology to determine an age-related reliability index that can be used to compare the relative likelihood of in-service failures among underground distribution feeders. It was developed for the Con Edison 27 kV and 13.8 kV distribution systems but is sufficiently generic to apply to any group of underground distribution feeders. Each feeder is represented by a combined reliability model of its individual components, including the following: cable sections-paper and solid dielectric insulated cables; cable joints-paper-to-paper, paper-to-solid dielectric and solid dielectric-to-solid dielectric insulated cable joints; and network transformers. The parameters of each component model are determined based upon historical failure data according to age. The confidence level associated with the prediction is also determined, and a brief description of the computer program developed and its application to Con Edison's Yorkville 13.8 kV primary distribution network are provided.

Several equations are presented to discuss the analytical basis for the model. Table 1 displays the quantity of failed components of age 5 or less, greater than 5 years, and unfailed components at the end of the study window. The table displays the number of failures of transformers, paper cables, solid cables, paper paper joints, paper solid joints, and solid solid joints for 13.8 kV and 27 kV systems. Tables 2 and 3 expand upon the data in Table 1 for failed components f age 5 years or less or greater than 5 years, respectively. Beta (shape parameter) and lambda (scale parameter) data for Weibull distributions are presented. Figures 2 and 3 display actual and Weibull curves for the percentage of failures versus age at failure for 13.8 kV cable OA/FOT paper insulation and 13.8 kV OA/FOT solid solid, respectfully. Table 3 displays distribution feeder outage prediction data from the software package that performs the calculations for the model presented in the paper. The data presented include the feeder component number and the quality reliability index for transformers, cables, joints and the feeder age-related reliability index with 90% confidence limits. Appendix A contains a discussion regarding the journal article where more equations are presented. Figure 4 is also displayed as a comparison of near-term predictions of Equation 12 (from the paper) versus alternatives. Data from the initial estimate, test case, equation 12, and IEEE estimate are presented.

Search terms and ID: Cables, Technical, Equations, Journal Article, 93

Burges, 1983

Burges, L.H.

“Benefits of Quantitative Analysis in the Assessment of Electrical System Reliability,” Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 7-12, IEE, London, United Kingdom

This article discusses the benefits of quantified reliability analysis. It looks specifically at systems configuration and whether or not it will meet some predetermined target reliability. Looks at reliability parameters such as causes of faults, is a particular piece of equipment more prone to failure than others, etc.

The article outlines a methodology, and has very brief comments regarding trip relays. Uses a failure rate of trip relays of 0.05 faults/year.

Search terms and ID: System, Technical, Data, Proceedings, 10

Cabane, 1973(1)

Cabane, E.; Carton, D.; Denoble, R.; Guillevic, A.; Latil, L.; Michaca, R.

"Reliability of switchgear and transformers in distribution substations," CIRED 2nd International Conference on Electricity Distribution, 1973, 36-48, IEE, London, UK

Two separate issues are addressed in this paper. In part one, failures in metal-enclosed switchgear are examined. The issue is the appropriate rate of maintenance considering the cost of maintenance and cost of undelivered energy. It begins with a review of stresses on switchgear. It then presents costs and failure rate information and calculates the cost of alternative maintenance strategies. Part two reports on tests of new 25, 50, and 100 kVA transformers. These transformers were subjected to impulses of 47.5 kV up to 160 kV to test their response to lightning impulses. The failure rates and equations for probability of failure are reported and compared to earlier designs.

In Part one, fault rates on feeders are listed. These are for a 70 km feeder fugitive faults 74/year, semi-permanent faults 10/year, and permanent faults 5/year. The breaker failure rate is 0.023 failures/year. Data sources or other details are noted provided. Part two presents failure data for the new transformers tested in detail. Based on the data they present equations for failure probabilities given the transformer rating and the impulse size.

Search terms and ID: Multiple, Technical, Data, Proceedings, 228

Cabane, 1973(2)

Cabane, E.; Carton, D.; Denoble, R.; Guillevic, A.; Latil, L.; Michaca, R.

"Reliability of switchgear and transformers in distribution substations," CIRED 2nd International Conference on Electricity Distribution, 1973, 36-48, IEE, London, UK

This paper begins with a review of the stresses on metal-enclosed switchgear in distribution substations. It then discusses the costs associated with this equipment including maintenance, repairs, undelivered energy costs. In the next section it examines transformers and tests that can be performed on transformers to assess their condition.

Provides data on the failures of transformers under application of high-voltages.

Search terms and ID: Switches, Causes, Monitoring, Proceedings, 266

Call, 1991

Call, H.J.; Beccue, P.C.; Murphy, D.A.

"Diagnosis and Treatment of Component Failure Using Bayesian Inference," Use of decision analysis model for making decisions under uncertainty is discussed for choosing whether or not to replace boiler tubes. Bayesian calculations are performed with DPL decision analysis software.

Qualitative description of quantitative methods. Examples of influence diagrams and decision tree diagrams are presented. For data generated by the analysis, Figure 8 displays life fraction distribution with priors and test results and Figure 9 displays expected value costs versus the service age of tubes.

Search terms and ID: Other, Technical, 84

Carr, 1992

Carr, J.; Godfrey, R.M.

"UNDERGROUND VERSUS OVERHEAD DISTRIBUTION SYSTEMS," CEA No. 274 D 723, 1992, October, CANADIAN ELECTRICAL ASSOCIATION, Montréal, Québec

The selection between underground and overhead distribution systems is often based only on a comparison of the first costs. This report presents data and analysis techniques that incorporate all life cycle costs in the comparison. The report also outlines the many qualitative factors involved in selecting the type of distribution system and through an extensive consideration of aesthetic factors indicates the potential of hybrid approaches which avoid problems of overhead systems at a fraction of the cost of fully underground construction. The concepts are illustrated by case studies involving rural, suburban and urban applications, which involve both new development and reconstruction.

Appendixes contain cost and reliability data as well as background information and analytical details. Three case studies are presented which demonstrate the analytical selection process for a rural distribution system, a new suburban residential subdivision and the redevelopment of an urban area with a mixed residential and commercial load.

Extensive failure rate data is presented in Appendix A. Surveys were sent to Alberta Power Limited, Edmonton Power, Newfoundland Power, TransAlta Utilities, Toronto Hydro, and Winnipeg Hydro concerning equipment failure rates. Results of these surveys are tabulated in Tables A2.1 through A2.2. Table A2.1 deals with primary cable. Component types are rural 1 phase urban 1 phase, rural 3 phase, and urban 3 phase. Data recorded include: Voltage Class, insulation type, conductor type, jacket material, typical age, type of installation, installation technique, expected useful life, length in service, failures per year, failure rate, service restoration time, repair time, and maintenance cost per event. Table A2.2 deals with separable connectors. Component types are rural 1 phase urban 1 phase, rural 3 phase, and urban 3 phase. Data recorded include: Voltage Class, contin. current, elbow duty, age, number in service, failures per year, failure rate, service restoration time, repair time, and maintenance cost per event. Table A2.3 deals with underground transformers. Component types are rural residential, urban residential, commercial, and industrial. Data recorded include: Voltage Class, transformer phases, transformer installation, transformer insulation, typical transformer size, protection combination, useful life, number in service, failures per year, failure rate, service restoration time, repair time, and maintenance cost per event. Table A2.5 deals with overhead primary line installations. Component types are rural 1 phase urban 1 phase, rural 3 phase, and urban 3 phase. Data recorded include: Voltage Class, conductor type, age, typical framing, typical pole height, typical span length, Typical system configuration, useful life, length in service, failures per year, failure rate, service restoration time, repair time, and maintenance cost per event. Table A2.6 deals with overhead transformers. Component types are rural residential, urban residential, commercial, and industrial. Data recorded include: Voltage Class, transformer phases, transformer insulation, typical transformer size, protection combination, useful life, number in service, failures per year, failure rate, service restoration time, repair time, and maintenance cost per event. Table A.3.1 lists published data collected from other sources. Components covered in the table are: Cable at 1 yr, 1 ph-XLPE; Cable at 10 yr, 1 ph-XLPE; Cable at 15 yr, 1 ph-XLPE; Cable, 1 ph-KWWPE; 3-phase cable, 3ph-PILC; 1-phase cable, 1 ph-XLPE; Cable, 3ph-PILC; Cable at 0.76 cover, 1 ph-XLPE; Cable at 0.94 cover, lph-XLPE; Cable at 1.12 cover, lph-XLPE; Cable, lph-XLPE; -dig ins, 1 ph-XLPE; -other, 1 ph-XLPE; Typical open wire, 3ph; 12 kV primary, 3ph; Separable connector; Elbows; Splices; Switch; 3-phase switch; Circuit breaker; 12 kV recloser; Distribution Tx, lph Padmt; Distribution Tx, 3ph Padmt; Distribution Tx, 1 ph Sub; Distribution Tx, 1 ph/O/H; Distribution Tx, 1 ph/Q/H; Distribution Tx, 1 ph/O/H; 7.2 kVTx; Fuse; Lightning arrestor; Secondary. Information provided on each component includes Failure Rate, Repair Rate, Maintenance Outage Rate, Maintenance Downtime, Source, and Year(s) of Statistics.

The cover page, abstract, executive summary, table of contents, Table A3.1, and the references for Table A3.1 are found in the reliability reference library. The entire report can be found in the EPRI library."

Search terms and ID: Multiple, Financial, Data, Report, 269

CEA, 1999

CEA

"1998 Annual service continuity report on distribution system performance in Canadian electrical utilities composite version," 1999, May, Canadian Electricity Association, Montreal, Quebec

This is a statistical report covering 32 Canadian utilities and 7 International companies for the year 1998 with comparisons to 1997 and to the 1994-1998 5-year averages. The data reported are mainly indices of reliability from a customer perspective, for example, SAIFI, SAIFI (momentary), SAIDI, and CAIDI. Also reported are the following indicators of causes: unknown/other, scheduled outage, loss of supply, tree contacts, lightning, defective equipment, adverse weather, adverse environment, human element, and foreign interference. The bulk of the materials reported are averages for Canada. Several charts do show the data on a utility-by-utility basis, but without the individual utilities being identified.

No data is reported on specific equipment.

Search terms and ID: System, Data, Causes, Report, 224

CEA, 1998

CEA

"Forced outage performance of transmission equipment," 1998, July, Canadian Electricity Association, Montreal, Quebec

This report contains extensive data on transmission outages from the CEA's Equipment Reliability Information System (ERIS). Detailed data on lines, transformer banks, circuit breakers, cables, synchronous and static compensators, shunt reactors, shunt capacitor, and series capacitors, as well as their subcomponents is given. Failure rates and duration information is given by outage type, cause, and voltage level. The data is compiled from 11 participating Canadian utilities.

The report is issued every 5 years. Transmission is defined as above 110 kV. No data is provided on an age basis. An up to 109 kV classification is provided for shunt reactor banks, shunt capacitor banks, and series capacitor banks.

Search terms and ID: Multiple, Data, Report, 221

Chang, 1979

Chang, N.E.; Gilmer, D.L.; Mciver,J.C.

"Cost-Reliability Evaluation of Commercial and Industrial Underground Distribution System Design, Conference Paper Discussion for," IEEE Power engineering society discussions and closures of abstracted papers from the winter meeting, 1979, February 4-9, IEEE, New York, New York

This paper contains questions and replies regarding a paper that we do not have. Without the paper they are of little or no value.

Search terms and ID: System, Other, Proceedings, 254

Chapel, 2000(1)

Chapel, Steve; Morris, P.E. ; Downs, C.; Feinstein, C.D.

"Customer Needs for Electric Power Reliability and Power Quality: EPRI White Paper," 1000428, 2000, November, EPRI, Palo Alto, California

The report reviews the current state of knowledge about customers' needs for electric power reliability. It includes descriptions of methodologies for assessing outage costs, quantitative and qualitative results of studies, description of a framework for estimating the value of reliability, a comparison with traditional approaches to measuring reliability, and a bibliography.

Search terms and ID: Non-specific, Financial, Report, 1

Chapel, 2000(2)

Chapel, S.; Morris, P.; Feinstein, C.

"Managing Aging Distribution System Assets," 1000422, 2000, December, EPRI, Palo Alto, California

Describes research done to identify and develop methods for making decisions about aging assets in electric distribution systems. The problem of aging assets has become more important because of the increasing emphasis on reliability and customer services. Distribution assets, such as substation transformers, feeders, poles, wires, breakers and other equipment are subject to failure. The probability of failure is dependent upon at least four factors: loading, age, maintenance, and external conditions. The decisions that distribution system managers must make include when to replace an asset when to repair or overhaul an asset, when to maintain and asset, and when to do nothing. The optimal decision depends on the four factors listed above combined with the costs of various alternatives. The methods being developed seek and optimal (least-cost) policy for maintenance and replacement of electric distribution assets.

The report begins with a discussion of methodology, an overview of the aging process, data, and the currently implemented tools. In the next section, a brief literature review is review is presented. The last two sections review analytic procedures and propose an analytic procedure."

Distribution assets include: substation transformers, feeders, poles, wires, breakers, and other equipment. Probability of failure is dependent upon at least four factors: Loading, age, maintenance, and external conditions Actions are summarized as replacement, repair, maintenance, and do nothing. Methods seek a least cost alternative

Search terms and ID: Non-specific, Financial, Technical, Report, 2

Chapel, 2000(3)

Chapel, S.; Morris, P.A. ; Cedolin, R.; Feinstein, C.D.

"Reliability of Electric Utility Distribution Systems: EPRI White Paper," 1000424, 2000, October, EPRI, Palo Alto, California

"The report describes what is known with respect to the reliability of electric power distribution systems. It describes the state of knowledge, tools and practices for distribution system reliability. The report is based on an extensive literature survey, which investigated papers, reports, books and electronic media. The report discusses definitions of reliability; utility planning practices; the role of regulators; utility power quality approaches; and existing methods for reliability analysis. The main conclusion of the report is that, although the theory of reliability of systems is well developed, the application of analytical techniques to distribution systems planning is limited. There is no single, generally available, methodology that distribution planners can use to answer the questions associated with reliability-based planning.

The report provides: an excellent summary of the state-of-the-art in reliability, suggestions for new approaches, and an extensive literature review."

Search terms and ID: System, Financial, Technical, Report, 48

Chen, 1995

Chen, Rong-Liang; Allen, Kim ; Billinton, R.

"Value-Based Distribution Reliability Assessment and Planning," IEEE Transactions on Power Delivery, 1995, 22-Jan, 10, 1, IEEE

This paper discusses VBDRA (value-based distribution reliability assessment) and its 1992 application at Scarborough Public Utilities Commission (SPUC) to assess feeder projects. VBDRA combines distribution reliability indices with customer interruption costs at load points. The reliability assessment model follows that in the Guide to Value Based Reliability Planning, also written by Billinton. Outage exposure is assessed both by the load point and component failure techniques. The analytic results from these two techniques for the total customer interruption costs are proven to be algebraically equivalent. However, the load point technique is found to be much faster computationally. The data requirements for an assessment are outlined. Feeder level reliability indices are defined and calculated and combined with customer interruption costs to calculate relative benefits of a number of competing capital-investment feeder projects at SPUC. SPUC's own historical fault data, and that from North York Hydro, and customer interruption costs from previous work are used. The resulting project prioritization was used by SPUC in its capital budget planning, and a reliability assessment was repeated a couple of years later showing an improvement in overall customer interruption costs.

Customer interruptions are a function of both equipment failure rates and failure durations. VBDRA application as a spreadsheet macro is demonstrated."

Table 1 lists equipment failure rate and durations (columns) for cable, elbow, fuse, fault interrupter, overhead line, splice, switch, and transformer.

References for the data are:

W.F. Horton, S. Goldberg and R.A. Hartwell, "A Cost/Benefit Analysis in Feeder Reliability Studies", IEEE Transactions on Power Delivery, Vol.4, No.1, 1989, pp. 446-452.

S.R. Gilligan, "A Method for Estimating the Reliability of Distribution Circuits", IEEE Transactions on Power Delivery, Vol.7, No.2, 1992, pp.694-698.

W.F. Horton, S. Goldberg and C.A. Volkman, "The failure Rates of Overhead Distribution System Components", Proceedings of the Transmission and Distribution Conference, IEEE, Dallas, Sept.1991, pp. 713-717 15.

W.F. Horton, S. Goldberg and C.A. Volkman, "Determination of Failure Rates of Underground Distribution System Components from Historical Data", Proceedings of the Transmission And Distribution Conference, IEEE, Dallas, Sept.1991, pp.718-723.

North York Hydro, "1991-1992 Underground Rebuilds Plan", November 20, 1989.

Shortest failure durations have the highest customer interruption costs per hour because momentary power losses have the highest costs per hour."

Search terms and ID: Multiple, Financial, Data, Proceedings, 44

Chowdhury, 2000

Chowdhury, A.A.; Koval, D.O.

"Current practices and customer value-based distribution system reliability planning," Conference record of the 2000 IEEE Industry Applications Conference, 2000, 2, IEEE

Utilities are increasingly recognizing that the level of supply reliability planned and designed into a system has to evolve away from levels determined basically on a technical framework using deterministic criteria, and towards a balance between minimizing costs and achieving a sustainable level of customer complaints. Assessment of the cost of maintaining a certain level of supply reliability or making incremental changes therein must include not only the utility's cost of providing such reliability and the potential revenue losses during outages, but also the interruption costs incurred by the affected customers during utility power outages. Such a cost-benefit analysis constitutes the focal point of the value-based reliability planning. Value-based reliability planning provides a rational and consistent framework for answering the fundamental economic question of how much reliability is adequate from the customer perspective and where a utility should spend its reliability dollars to optimize efficiency an satisfy customers' electricity requirements at the lowest cost. Explicit considerations of these customer interruption costs in developing supply reliability targets and in evaluating alternate proposals for network upgrade, maintenance, and system design must, therefore, be included in system planning and design process. The paper provides a brief overview of current deterministic planning practices in utility distribution system planning, and introduces a probabilistic customer value-based approach to alternate feed requirements planning for overhead distribution networks.

Contains no useful data. A fairly general discussion of value-based planning with a very simple example. May be of interest as an alternative presentation of the topic.

Search terms and ID: Non-specific, Financial, Proceedings, 232

Choy, 1996

Choy, Siang-Ying; English, John R. ; Landers, T.L.; Yan, L.

“Collective approach for modeling complex system failures,”1996 proceedings annual reliability and maintainability symposium, 1996, 282-286

This paper defines the functional requirements of a DSS necessary to serve as a working tool in assisting the reliability engineer in equipment repair/replacement management of material handling equipment.

Focuses on modeling not data

Search terms and ID: System, Technical, Proceedings, 60

Collard, 1980

Collard, Steve; Paracos, Edward; Kressner, A.

“Root Cause Failure Analysis In Electrical Transmission and Distribution Equipment,”1980 Proceedings Annual Reliability and Maintainability Symposium, 1980, January 22, IEEE

"The paper discusses root-cause failure analysis on electric power equipment. This analysis was motivated by lack of failure analysis activity beyond the warranty period of electric equipment, and the reluctance of the manufacturers to get involved in such activity. The paper defines failure analysis as the performance of a detailed study to establish the failure mode, mechanism and cause-and-effect of each experienced failure. The conceptual framework for root-cause failure analysis is based on an understanding of the nature of the equipment failure: (1) every failure has a cause; (2) unless the cause is corrected the failure will occur again; (3) as stresses on a component increases so will the failure probability; (4) eliminating the cause as the only way to avoid future failures; (5) thorough examination and analysis of failed part to determine the cause of failure; and (6) if a specific failure occurs from a natural cause it can be induced in the laboratory.

For each analysis the paper provides a summary of the type of equipment, findings, cause of failure and recommendations. The analysis is performed on network protector motors failures, high voltage circuit breaker O-ring seal failures, and network primary cable and joint failures. The paper concludes by pointing that root-cause failure analysis is now an established function at Con Edison. The paper is interesting from the empirical point of view, but has no modeling value for us.

Article supports failure analysis as a means to improve reliability of equipment and to increase availability. Failure analysis also allows suppliers to improve equipment design."

Low-bid procurement has caused some suppliers to abandon failure analysis and to design equipment to survive the warranty period.

Search terms and ID: Multiple, Causes, Journal Article, 40

Commonwealth Edison, 1998

Commonwealth Edison

"Commonwealth Edison Co. 1998 Report on Reliability to the Illinois Commerce Commission," 1998, iii-99, Illinois

Report submitted by the Commonwealth Edison Company (ComEd) to the Illinois Commerce Commission regarding transmission reliability rules. Report summarizes ComEd outage causes for 1998.

Table 3 lists the number of planned and unplanned interruptions for the system. Table 4 lists the number of planned and unplanned interruptions in the Chicago area. Table 5 lists the number of planned and unplanned interruptions in the Northeast area. Table 6 lists the number of planned and unplanned interruptions in the Southern area. Table 7 lists the number of planned and unplanned interruptions in the Northwest area. Table 8 provides detailed data regarding controllable interruptions for Chicago, the Northeast, Southern, Northwest, and the system. For Tables 4 through 8, the total number of interruptions is provided, as well as the average interruption duration. Planned interruptions include those scheduled for construction, maintenance, or repair. Unplanned interruptions are caused by other utilities or suppliers, ComEd/Contractor personnel errors, customers, the public, weather, animals, trees, overheated equipment, underground equipment failures, international, transmission and substation equipment related, or other. Figures 4 through 10 display the distribution of lightning arresters, feet of buried cable, feet of overhead distribution conductors (aluminum and copper), number of distribution poles, number of crossarms, number of meters, and capacity of distribution transformers versus their respective ages. Table 9 presents a summary of the number of interruptions for the Chicago, Northeast, Southern and Northwest operating areas. Table 10 provides transmission expenditures and Table 11 distribution expenditures in 1998 for the ComEd system. Tables 12 and 13 present customer satisfaction data. Table 14 lists customer reliability complaints regarding sustained interruptions, momentary interruptions, low voltage and high voltage complaints for Chicago, Northeast, Southern, Northwest and the system as a whole. Table 15 presents CAIDI, CAIFI and SAIFI data for Chicago, Northeast, Southern, Northwest and the system as a whole. Tables 16 through 19 provide a list of the worst performing circuits in 1998 or the Chicago, Northeast, Southern and Northwest areas in terms of CAIDI, CAIFI and SAIFI. Following Tables 16 through 19 is a detailed breakdown of the worst 1% of Chicago operating area circuits as measured by the CAIDI index. The detailed information includes the circuit identification, interruption date, number of customers affected, duration, cause, date of last inspection, date of last tree trimming and a description of the work to repair the circuit, as well as the cost of the repair. Such data is provided for 19 circuits. Next, the worst 1% of Chicago operating area circuits as measured by the CAIFI/SAIFI indices is presented. Each of 19 circuits is documented with each interruption date, number of customers affected, the duration and cause. The date of last inspection, date of last tree trimming, and a work description/cost of work are also chronicled. Similar data is presented for the Northeast operating area (17 CAIDI and CAIFI/SAIFI data entries), Southern operating area (8 CAIDI and CAIFI/SAIFI data entries) and the Northwest operating area (7 CAIDI and CAIFI/SAIFI data entries). Table 20 provides the peak demand and projected load (in Megawatts) for each of the four operating areas (and the corresponding total) for 1998 and projected numbers for 1999, 2000 and 2001. Table 21 presents the peak loading on each distribution transformer at or above 90% for the Chicago, Northeast, Southern and Northwest operating areas. The transformer ID, normal rating, emergency rating, 1998 peak loading (all in MVA), percent of normal rating and percent of emergency rating are displayed. Table 22 presents the distribution transformer loading corrective actions for transformers in each of the four operating areas. Table 23 presents the peak loading on each transmission transformer at or above 90%. Specific data include the ComEd operating area, station, transformer ID, normal rating (in MVA), emergency rating (in MVA), 1998 peak loading (in MVA), percent of normal rating and percent of emergency rating.

Search terms and ID: System, Data, Causes, Report, 90

Connor, 1966

Connor, R.A.W.; Parkins, R.A.

"Operational Statistics in the Management of Large Distribution Systems," Proceedings of the Institution of Electrical Engineers, 1966, November, 113, 11, 1823-1834, IEE, London, UK

In order to manage a large distribution system in the best manner, it is considered necessary to have comprehensive, accurate and up-to-date records of the number and types of equipment items in service, together with properly analyzed records of their performance.

With the advent of nationalization of the supply industry in 1948, and the formation of a small number of large undertakings, it became possible to study the performance of large networks in a manner not previously possible. The paper gives details of the way in which the necessary data are collected, analyzed and used in one Area Board. Details are given of some of the conclusions reached to date of some other problems, which are being studied, and some observations are made on reliability and security of supplies.

Although some problems do not lend themselves to analytical treatment of the type described, many do, and it is contended that a great deal of valuable information on design, construction, operation and maintenance of networks can be obtained from the analysis of properly compiled data."

The paper was written in 1965 and generally covers data during the preceding 14 years (1951-1965). Covers networks with nominal system voltages of 2-33kV. No data is provided relating failure rates to aging. However, considerable data is provided on failure rates. Table 1 provides data on overhead line faults. Columns indicate the system voltage and method of earthing, 2 to 33 kV in six intervals with earthing designated as s.r.o. or a.s.c.. Rows represent failure mechanisms and total failures. The failure mechanisms include: lightning, abnormal weather conditions, growing trees, windborne materials, human agency, birds, conductor failure, joint or clamp failure, jumpers, binders, insulation failure, failure of support, failure of pole-mounted switch on fuse gear, miscellaneous, and unknown. Table 2 provides data on underground cable failures. Columns indicate the system voltage and method of earthing, 2 to 33 kV in six intervals with earthing designated as s.r.o. or a.s.c.. Rows represent failure mechanisms and total failures. The failure mechanisms include: human agency, mechanical damage to sheath, corrosion, insulation failure, pole-box failure, joint failure, ground subsidence, miscellaneous. Table 3 provides data on failures of underground cable terminations and joints. Columns are provided for 11kV and 33kV. Rows designate cable joint failures per 100 miles per annum, cable joint failures per 100 joints per annum, cable terminators failures per 100 miles per annum, cable terminators failures per 100 joints per annum, pole boxes failures per 100 miles per annum, pole boxes failures per 100 joints per annum. Table 4 presents transformer data. Columns indicate the system voltage and method of earthing, 2 to 33 kV in six intervals with earthing designated as s.r.o. or a.s.c.. Rows represent failure mechanisms and total failures. The failure mechanisms include: bushing failure, winding failure, oil quality, overload, tap-change mechanism, miscellaneous. Table 5 presents switchgear failure rates per 100 switchgear units. Rows represent failure mechanisms and total failures. The failure mechanisms include: circuit-breaker failures, tripping or closing mechanisms, A.R. tripping or closing mechanism, current transformers, voltage transformers, other failure of outdoor switchgear, other failures of indoor switchgear, small wiring and auxiliary switches, failure of metal clad fuse switch, failure of metal clad oil-immersed isolator or switch, failure of air-break isolator, miscellaneous. Table 6 presents protective-gear fault causes. Columns are faults per 100 switchgear units per annum and % of total number of faults. Rows are causes. The causes include: relays and components, Incorrect settings, Failure of trip supply, A.C. trip circuit and t.l. fuses, Wiring defects, Pilot cables, Incorrect connections, Incorrect circuit diagram, Interference with secondary wiring, Testing errors, Vibration or mechanical shock, Incorrect characteristic, Unknown at time of original report, All causes

Search terms and ID: Multiple, Data, Causes, Journal, 260

Contaxis, 1989

Contaxis, G.C.; Kavatza, S.D. ; Vournas, C.D.

"Interactive Package for Risk Evaluation and Maintenance Scheduling," IEEE Transactions on Power Systems, 1989, May, 4, 2

This paper describes an interactive computer package for evaluating the risk level of a power system and for scheduling the preventive maintenance of the system's generating units. The risk is calculated via the loss of load probability (LOLP). The paper reviews solutions for LOLP calculation based on convolution of simple bimodal probability distributions that each describe the capacity outage probability associated with (binary) variable of capacity (0 or full capacity) for each generator (the convolution over these bimodal distributions gives the total probability distribution associated with system capacity). The objective function of the maintenance scheduling is minimization of the annual system risk while all the physical and technical constraints imposed by the system and the planning practices are met. The paper considers optimization of this objective function (subject to constraints) with respect to maintenance scheduling of the generators. Pointing out the difficulties and state of the art as related to calculation of LOLP and the integer nature of maintenance scheduling optimization, the paper introduces two additional approximate solutions (based on effective reserve and levelized risk levels) for the posed problem. A demonstrative case study has been considered.

"

LOLP helps calculate the capacity outage probability table (COPT). LOLP can be determined several different ways.

Search terms and ID: Generators, Maintenance, Technical, Journal Article, 29

Dalabeih, 1995

Dalabeih, D.M.; Jebril, Y.A.

"Determination of Data for Reliability Analysis of a Transmission System," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 19-23, IEE, Norwich, UK

Statistical analysis of reliability data from 1989 to 1993 for the 132 kV Jordanian Transmission System.

Table 2 provides data for outage types, duration and number of data points for 132 kV transmission line outages, 341 data points. Table 3 provides component forced outage rates for 132/ kV transformers, 132 kV circuit breakers and 132 kV busbars (1505 T-unit year of exposure). The table displays outages/ unit year, number of outages observed, T-unit year of exposure. Table 4 lists component scheduled outage rates132/ kV transformers, 132 kV circuit breakers and 132 kV busbars (655 T-unit year of exposure), Table 5 lists component forced outage duration for 132/ kV transformers, 132 kV circuit breakers and 132 kV busbars (655 data points), Table 6 lists component scheduled outage duration for 132/ kV transformers, 132 kV circuit breakers and 132 kV busbars (476 data points),

Search terms and ID: Multiple, Data, Proceedings, 65

Darveniza, 1996

Darveniza, M.; Mercer, D.R.; Watson, R.M.

“Assessment of the reliability of in-service gapped silicon-carbide distribution surge arresters, An,” IEEE Transactions on Power Delivery, 1996, October, 11, 4, 1789-97, IEEE

Although electricity authorities no longer purchase gapped silicon carbide arresters, they still form the majority of the very large number of distribution arresters in service in Australia and many other countries. Most of the arresters of this type are now over ten years old and many are much older. So the question must be asked-what is to be done with this ageing and outdated class of arresters? Extensive Australian studies in the 1960s had revealed that internal degradation resulting from inadequate seals was the predominant cause of failure of gapped silicon carbide arresters. This paper describes the results of a recent investigation. Electrical testing showed that after about 10 years of service, there is a marked upturn in the number of arresters with unsatisfactory insulation resistance, and after about 13 years of service, a marked upturn in the number of arresters with reduced power frequency spark over level. Inspection of the internal components of dismantled arresters confirmed that the likelihood of significant degradation increased markedly with years of service, and was evident in almost 75% of arresters with 13 years or more of service. The authors therefore recommend that modern metal oxide arresters progressively replace all gapped silicon carbide arresters with 13 or more years of service.

The data is somewhat hard to interpret. It concerns the performance of surge arrestors in response to laboratory testing rather than field performance. The sample was 365 surge arrestors from eight Australian utilities. Voltage ratings ranged from 9kV to 24kV, about 80% had a current rating of 5kA while the remainder were rated at 10kA. The arrestors were subject to 5 tests. Figure 1 indicates how many of the arrestors passed or failed the tests. All possible combinations of pass-fail are reported. Table 2 presents failure rates by age. A discussion note points out the unreliability of several of the tests that were conducted.

Search terms and ID: Other, Data, Causes, Journal Article, 234

Dedman, 1990

Dedman, J.C.; Bowles, H.L.

"Survey of URD cable installed on rural electric systems and failures of that cable, A,"1990 Rural Electric Power Conference, 1990, D2-1 -- D2-7, IEEE, New York, NY

Several surveys have been conducted with the purpose of determining the history of failure of underground power cables. Typically, these surveys are used to compare data related to cables of various types or installation conditions. The Rural Electrification Administration (REA) has determined that most of the studies have not supplied valid or meaningful information, because neither the vintage of the cables nor their age at failure was considered. In 1988 and 1989, REA conducted a survey that supplied results that are both valid and meaningful. Analysis of the data reported by over 100 rural electrical cooperatives revealed trends related to several variables, such as insulation material and thickness, jacketing, conductor type, and installation methods. The cumulative total of failures, to date, of the cable installed in each year since 1970 was calculated and broken down according to the same variables. The results of the survey are discussed, and recommendations concerning ways that electric utilities can effectively use the results in considering replacement of aged cables are presented.

This study was initiated in 1998. The primary goal of the study was to associate cable failure to the vintage of the cable and its age at failure. Reports from 105 systems were collected. Many cable and installation characteristics were recorded in the survey. Data relevant to year of installation, cable jacketing, insulation material, insulation thickness, burial method, and stranding type are reported in this summary.

Figure 1 shows year versus total cable installed. Figure 2 shows year installed versus cumulative failures per 100 miles. Figure 3 shows % cable installed bare, jacketed or unknown versus year. Figure 4 shows cumulative failure per 100 miles versus year installed for both bare and jacketed cable. Figure 5 shows % cable using different insulation materials. Figure 6 shows cumulative failure per 100 miles versus year installed for each insulation material. Figure 7 shows % cable installed with different insulation thickness. Figure 8 shows cumulative failure per 100 miles versus year installed for each insulation thickness. Figure 9 shows % cable installed with different cable burial methods. Figure 10 shows cumulative failure per 100 miles versus year installed for each burial method. Figure 11 shows % cable installed with different conductor stranding types. Figure 12 shows cumulative failure per 100 miles versus year installed for each stranding type."

Search terms and ID: Cables, Data, Causes, Proceedings, 236

Degen, 1995

Degen, Wolfgang

"Design for Reliability Methodology and Cost Benefits in Design and Manufacture," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 61-65, IEE, Norwich, UK

Paper discusses the importance of quality and reliability in switchgear and the improvements over time in reliability.

Paper does not specifically discuss reliability and replacement, but it does provide some useful data. The sample size and timeframe for the data are not specified. Table 1 provides data for failure rates per 100-cb years for CIGRE and Siemens switches. The data further provides the percentage of failures among major causes. A useful reference mentioned is the Second International Enquiry into Reliability of High Voltage Circuit Breakers (CIGRE 1988-1991).

Search terms and ID: Switches, Data, Causes, Proceedings, 67

DeLima, 1998

DeLima, Fabio

“Discussion of "transmission equipment reliability data from Canadian Electrical Association",” IEEE transactions on industry applications, 1998, March, 34, 2, 415, IEEE

Comments on the meaning and usefulness of the data presented in an earlier paper.

"Provides two useful references:

D.O. Koval, IEEE Trans. Ind. Applications, vol 32, pp. 1431-1439, Nov/Dec 1996

C.R. Heising, ""Worldwide reliability survey of high-voltage circuit breakers, ""IEEE Ind Applications Mag., vol 2, pp65-66, May/June 1996

"

Search terms and ID: Multiple, Other, Journal Article, 54

Dixon, 1983

Dixon, G.F.L.; Hammersley, H.

“Reliability and Its Cost on Distribution Systems,” Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 81-84, IEE, London

Paper discusses reliability of British distribution networks and provides data regarding reliability costs, investment strategies and aids in decisions for drastic changes.

This may serve as a good background for developing a model for the cost of failures, but doesn't address likelihood of component failures explicitly. Systems are discussed, but no components are specifically discussed.

Search terms and ID: System, Financial, Design, Proceedings, 14

Dougherty, 2000

Dougherty, Jeff G.; Stebbins, Wayne L.

“Power quality: a utility and industry perspective,” Energy User News, 2000, March, 25, 3, 12

Provides a long list of quality problems and discusses the causes and proposes some solutions. Problems noted include: sags and swells, long duration variations, impulsive transients, oscillatory transients, harmonic distortion, voltage fluctuations, and noise.

Search terms and ID: Multiple, Causes, Design, Journal Article, 204

Douglas, 1995

Douglas, J.A.K.; Randles, N.J.L.; Magee, D.; Bailie, H.D.

“Ranking of Design Criteria to Improve Rural Network Performance,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 145-150, IEE, Norwich, UK

Model based on probabilistic circuit modeling is used to evaluate different design criteria and the corresponding technical benefits. Improvements are aimed at security and availability indices.

Data synthesized by a technical model. Table 1 displays data predicted by the model and actual performance in terms of customer hours lost, CML, customers affected, and interruptions per 100 customers, faults and faults per 100 km. States that the UK average is 12.5 faults per 100 km.

Search terms and ID: System, Design, Model, Proceedings, 72

East Midland Electricity, 2000

East Midland Electricity

“Quality of Supply Report (1999/2000),” 2000, East Midland Electricity

Yearly supply performance report. Contains descriptions of mechanical and natural failures by location.

Data is divided by region. 11 kV unplanned minutes lost by cause data is presented for Coventry and Warwickshire, Derbyshire, Leicestershire, Lincolnshire, North Hamptonshire and Nottinghamshire. Condition Report 9 (page 26) displays supply interruption data by location for low voltage cutouts and mains and high voltage overhead and underground lines. Pages 28 to 30 display the performance of 11 kV lines by location.

Search terms and ID: System, Data, Report, 126

EBASCO Services Inc., 1987

EBASCO Services Inc.

“Electric Distribution Systems Engineering Handbook,” 1987, McGraw Hill Publication Co., New York, New York

The goal of this handbook is to survey the entire field of distribution system engineering. It is a large text and provides detail on many engineering tasks; however, it provides minimal depth on advanced issues. The topics covered include: planning and design criteria; economics standard specifications, codes, and regulations; radial primary systems; and utilization equipment and load characteristics. System reliability is discussed in Chapter 1, Section E161.

"Only the cover page, contents, and reliability data from this book is found in the reliability library. The book itself is available in the EPRI library.

The book provides very limited reliability data. One table is presented in the context of an example of reliability calculations. Table 2 on page 30 of Chapter 1, Section 161 presents the reliability data for distribution components. Data (columns) include survey period, failures per year, expected repair time, and maintenance outages per year, maintenance outage time. Components include (columns) 69/12kV transformer, 69kV lines, 69&12kV breakers, 69&12kV buses, 12kV recloser, 12kV tie feeder, 12kV primary, and 7.2kV transformer."

Search terms and ID: System, Technical, Financial, Book, 261

Edwin, 1983(1)

Edwin, K.W.; Dib, R. ; Niehage, U.

"Reliability Investigations for 110-kV Subtransmission Networks," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 73-77, IEE, London, United Kingdom

Overhead lines are subjected to atmospheric influences, and are thus frequently interrupted by one- or multi-phase faults. A method used to calculate reliability of subtransmission networks is presented and applied. It was determined that most simultaneous outages were due mainly in common-cause faults in double circuit transmission lines and simultaneous ground faults and the protection system failing to operate.

The data source is not specified beyond two German utilities. Neither a date for the data or sample size is provided. Table lists for Resonant neutral earthing and for low impedance neutral earthing and power transmission line, power transformer, busbar, busbar disconnector, and circuit breaker switch bay (rows) the following data: rate of independent forced outages, rate of independent scheduled outages, rate of primary outages due to simultaneous ground faults, common-cause outage rate of double circuit transmission line, conditional probability of sequential outage due to simultaneous ground faults, conditional probability of sequential outages due to protection system failing to operate, mean duration of forced outages, excluding outages due to simultaneous ground faults, mean duration of forced outages due to simultaneous ground faults, mean duration of scheduled outages, mean duration for common-cause outages of double circuit transmission lines, mean duration of switching actions (columns). The results of the failure affect the analysis for the following components of a subtransmission network: power transmission lines, power transformer, busbar, busbar disconnector, and circuit breaker switch bay.

Search terms and ID: Multiple, Technical, Data, Journal Article, 4

Edwin, 1983(1)

Edwin, K.W.; Nachtkamp, J. ; Siemes, B.

"Statistical Determination of the Availability of Important Components in the Electrical Power Supply," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September 19-21, 225, 115-118, IEE, London, United Kingdom

Confidence levels in probabilistic reliability models depend on the knowledge of component reliability. Data on several 110 kV grids is presented, but due to high reliability levels, it is difficult to form sufficient sample sizes.

" Data regarding reliability characteristics of overhead lines are presented in Table 4. The data was collected for 412 line/operation-years i.e. 9898km/operation-years from several inductively earthed 110 kV-grids, presumably in Germany. Data for these lines include: average forced outage frequency, average forced outage duration, % unplanned unavailability, confidence interval on % unplanned unavailability, % scheduled uptime, and % total expected availability.

The author notes,” "The average frequency of about one failure per line in two years is so small, that the data of all observed lines had to be evaluated together."" Also,” "Due to the high reliability level it is difficult to form samples with a sufficient size.""

Outage behavior is best approximated with a Weibull distribution. Reliable maintenance schedules can only be created if preventative maintenance provides for components subjected to heavy mechanical wear. A graph with repair-density versus repair duration data for turbines, boilers, and generators for a 150 MW coal unit are also provided."

Search terms and ID: Cables, Data, Technical, Proceedings, 16

EPRI, 1990

EPRI

“Cost-Benefit Analysis of Power System Reliability: Determination of Interruption Costs,” EL-6791, 1990, April, 1, 6-13 - 6-29, EPRI

European, Canadian and Brazilian reliability standards for generation are reviewed. At the transmission level, describes steps in planning and steps in quantitative reliability analysis. For the distribution system, lists sources of customer interruption and reviews reliability planning indices measuring customer reliability, feeders/circuits reliability, and system reliability. Voltage and current, fault current levels, and protective devices influence distribution system reliability. Investment decisions about system reliability regarding protection, system upgrades, facility design, maintenance, automation, etc., are described.

Table of system-wide outage costs for different countries is included, as well as a table of 1985 interruption statistics for U.S. facilities.

Search terms and ID: System, Financial, Technical, Report, 45

Farag, 1999

Farag, A.S.; Wang, C.; Cheng, T.C.; Zheng, G.; Du, Y.; Hu, L.

“Failure analysis of composite dielectric of power capacitors used in distribution systems,” Electric machines and power systems, 1999, March, 27, 3, 279-294, Taylor & Francis

This paper describes the study of the reliability of capacitor units installed and operated in distribution systems during the period 1980 through 1990. Failures of capacitor units in distribution substations can be very costly to the supply of reliable power to consumers. To enhance utility reliability, failure analysis, and rates, failure origin and physical damage causes were performed for these capacitor units. Two approaches, statistical and physical, were utilized in this study. In the statistical area, failure modes, reliability levels and failure causes are analyzed. The physical study mainly deals with the mechanism of deterioration of the composite dielectric. This paper models the capacitor's failure mathematical mode and calculates their failure rate. The results of the study of 2912 capacitor banks including 8736 capacitors installed at 153 distribution substations showed that the failure mode of capacitor units may be represented by Weibull distribution and each capacitor manufacturer has a different failure rate. Analysis showed that partial discharge properties are a critical indicator for the capacitor failure mechanism. Useful conclusions are presented both for power system operators and manufacturers. The methodology used in this study also applies to other equipment in the distribution system such as oil switches, transformers, and insulators.

"2912 banks including 8736 capacitors installed at 153 substations in LADWP 4.8kV distribution system. The rated voltage is 2.77 kV to ground and each single-phase capacitor is 150kVar. Three capacitors are banked to form a 450-kVar bank. Data from the period 1980 through 1990 have been analyzed. 541 failures were analyzed. All data presented is broken out by the four manufacturers of the capacitors; however, the manufacturers are not identified.

Table 1 indicates the cause of failure: main insulation breakdown, oil leaking, or broken bushing.

Figure two is a histogram of life times for the failed capacitors.

Figure three plots Y=mX-A where: Y=ln ln{1/[1-F(t)]}, X = ln(t), and A =ln(t0). F(t) is the Weibull distribution function. F(t)= 1-exp[(-t^m)/t0].

Table 3 presents for each manufacturer the sample size, the total number of failed capacitors, the parameters m and t0, and F(t).

Table 4 presents the results of the Kolmogrov Smirnov test. All distributions were acceptable by this test at the 5% level.

Table 6 provides the sample size, total number of failed capacitors, the failure rate function, and the mean time to failure.

Table 7 presents failure rate function, H(t), values for different years and the failure rate average calculated in two different ways. The first is based on the failure rate function. The second assumes that distribution function of capacitor life is and exponential distribution and that therefore the failure rate is constant.

The authors conclude that manufacturing has a significant impact on failure rate, and that oil switches because of a propensity to restrike are a poor choice for capacitor control.

Essentially the same paper was presented at the 7th International symposium on High Voltage Engineering."

Search terms and ID: Capacitors, Data, Causes, Journal Article, 231

Ferguson, 1987

Ferguson, R.P.

“Factors affecting the replacement of old transformers,” Revitalizing transmission and distribution systems, 1987, February 25-27, 273, 113-118, IEE, London, United Kingdom

Discusses the monitoring of transformers in detail. Monitoring activities and tests discussed include: inspection for external corrosion, insulation resistance by DC Megger, loss angle (tan delta) at 50 Hz, partial discharge, low voltage impulse tests, gas-in-oil analysis, reactance measurement, low voltage impulse tests,

Search terms and ID: Transformers, Monitoring, Maintenance, Proceedings, 203

Fletcher, 1995

Fletcher, P.L.; Degen, W.

“Summary of the Final Results and Conclusions of the Second International Enquiry on the Reliability of High Voltage Circuit-Breakers, A,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 24-30, IEE, Norwich, United Kingdom

Summary of circuit breaker reliability covering the period of January 1988 to December 1991. Data equivalent to 70708 circuit-breaker years from 132 utilities and 22 countries was included.

Table 1 provides the number of circuit-breaker-years included in the summary. The data is segregated by voltage, location (indoor/outdoor), and metal versus non-metal enclosed. Table 2 provides data regarding major and minor failures segregated by voltage. Data are per 100 circuit breaker years. There are two age classes Placed in service 1/1/78 to 1/1/83 and after 1983. Table 3 provides data for subassemblies. Table 5 provides data on the type of failure. Table 7 provides data on the causes of failure.

Search terms and ID: Switches, Data, Causes, Proceedings, 66

Ford, 1972

Ford, D. V.

"British Electricity Boards National Fault and Interruption Reporting Scheme--Objectives, Development and Operating Experience, The," IEEE Power Engineering Society Winter Meeting, 1972, Jan 30-Feb 4, 2179-2188, IEEE

Paper describes a nation-wide interruption data collection procedure for the UK. Data collected can be statistically analyzed to assist in matching organizational requirements with system fault repair needs.

Main purpose of the paper is to explain the process for collecting data. Some data is provided. Ranges of annual failure rates for overhead lines, underground cables, transformers and switchgear are presented. Failure rates for EHV, HV and MV/LV systems are presented. Failure rates for EHV systems with duplicated circuits are presented, as well as the average duration of interruptions according to types of equipment failures. Tables for variation in annual fault totals by cause; variation in lightning-caused faults; annual relationship between system reliability and customer interruptions; and six-year trend in interruption statistics are presented.

Search terms and ID: System, Data, Journal Article, 117

Freeman, 1996

Freeman, J.M.

"Analyzing equipment failure rates," International journal of quality & reliability management, 1996, April, 13, 4, 39

Presents data and analysis of failures in 11kV/415V pole mounted transformers. Lists failures by age, shows cumulative failure rates, and mean cumulative hazard. Also, discusses estimation of Weibull and Gumbel parameters from the data.

"Sample includes 252598 pole mounted transformers (PMT's) in England and Wales. Failure data is from the Electricity Council's NAFIRS (National Fault and Interruption Reporting Scheme for the years 1984-1985. The following tables are included: Table I - age, estimated number in England and Wales, recorded failures, hazard rate; Table II - service life, reverse rank, hazard, cumulative hazard; Table III - age, mean cumulative hazard.

Our copy is from the Internet and does not contain the mathematical expressions or the figures."

Search terms and ID: Transformers, Data, Equations, Journal Article, 205

Gilbert, 1994

Gilbert, Dennis

“Cable derating and nonlinear load panelboards,” EC&M Electrical Construction & Maintenance, 1994, February, Intertec

Suggests rules for derating cables when they are likely to experience harmonics. The paper does not relate economic factors to derating decisions. There is nothing methodologically interesting in the paper.

1993 NEC Note 1°C. requires cable derating due to harmonics

Search terms and ID: Cables, Design, Journal Article, 56

Gilligan, 1992

Gilligan, Sidney R.

“Method for Estimating the Reliability of Distribution Circuits, A,” IEEE Transactions on Power Delivery, 1992, April, 7, 2, 694-698, IEEE

The article presents a method to predict the relative reliability performance of distribution circuits and circuit segments. The method calculates with a spreadsheet the expected relative indices of annual interruption time and customer hours of interruption by multiplying factors for exposed length, exposure (to weather factors such as trees as well as inherent failure), conductor type, sectionalizing devices used, and customers connected. The results must be normalized somehow to be compared to actual performance. Customer outage values of $1.30/kWh residential, $7.42/kWh commercial, and $9.27/kWh industrial are used to assess the cost effectiveness of reliability improvement projects suggested by the method. The author states that no historical data is required. The factors, though, are empirical, based on general experience with circuit operation. The method examines only the post-substation, pre-secondary-transformer circuits of distribution systems. An application of the method to about 100 distribution circuits is discussed. Although less accurate than a method using historical data in a more sophisticated model, this seems like a valuable, quick and simple method. An answer to the question of whether a more sophisticated reliability modeling method is worth the effort and cost over the method presented here must be addressed. The paper exposes the key point that a field assessment of equipment environment is important to a reliability analysis, dependent on the fact that a large proportion of distribution outages are caused by external events (e.g., weather related problems). The method assumes the multiplicative factors are all independent and that the indexes are linear functions of each factor (e.g., annual interruption time is linearly dependent on conductor length and on fault rate for the exposure and that the fault rate per length is not dependent on length). This is reasonable if the analysis is only addressing interruptions caused by external events, but possibly not for inherent equipment failure. The paper doesn't address restoration time. This article is referenced in a paper by Billinton “Value-based distribution reliability assessment and planning,” 1/95, but the reliability prediction method isn't commented on there. It is just mentioned that failure rates are available in this paper.

Table II present fault rates for cable segments but the precise characteristics of the segments are unclear.

Search terms and ID: System, Technical, Financial, Journal Article, 63

Godfrey, 1996

Godfrey, R. M.; Billinton, R.

“Guide to Value-Based Distribution Reliability Planning, Volumes I and II,” 273 D 887, 1996, January, Canadian Electricity Association, Montreal, Quebec

Value-based reliability planning is a subset of a broader planning methodology known as Integrated Value-Based Planning, which seeks to deliver maximum value to customers considering all of their needs. Value-based distribution reliability planning focuses on the value realized by customers through the combination of electricity tariffs and reliability of service. This guide presents data and analytical techniques that may be used to integrate all utility costs and customer outage costs in a comprehensive decision-making framework. The concepts are illustrated by example and by case studies involving project planning in an urban commercial area and a rural area. Appendixes include a comprehensive bibliography on distribution reliability analysis and reliability worth investigation, as well as a summary of published outage costs and an overview of utility opinion on value-based distribution reliability planning.

"This report contains perhaps the best data we have found in any published source. The data sources are varied and differ for individual pieces of equipment. To quote the report,"“a summary of representative component reliability, which has been extracted and synthesized from a number of technical publications."" The data is contained in Tables 3.1-3 on pages 3-47 to 3-49. All tables specify the same data elements in columns. These are component, type/area, location (rural, urban, or any), year 1 failure rate, year 10 failure rate, terminal year failure rate, useful life, callout repair time, isolation repair time, repair/replace time, and source. Components covered are O/H line Xarm Rural, O/H Line Xarm Urban, O/H Line Armless Rural, O/H Line Armless Urban, O/H Line aerial Cable Urban, D.B. Cable XLPE Rural, D.B. Cable XLPE Urban, D.B. Cable TRXLPE-SF-PEEJ Rural, D.B. Cable TRXLPE-SF-PEEJ Urban, Cable in Duct XLPE Urban, Cable in Covered Duct XLPE Urban, Cable in C.E. Duct XLPE Urban, Cable in C.E. Duct TRXLPE-SF-PEEJ, Distribution Transformer Pole-mounted Rural, Distribution Transformer Pole-mounted Urban, Distribution Transformer Pad-mounted Rural, Distribution Transformer Pad-mounted Urban, Distribution Transformer Submersible Rural, Distribution Transformer Submersible Urban, Circuit Breaker, Reclosers, Fuse, Switch, Cable Elbow, Cable Splice, Lightning Arrestor.

The authors note, "This data appears reasonable and internally consistent, but it must be recognized that this data is based on selective reporting from utilities, in different jurisdictions, based on outage reporting systems which may define different events in different ways. As such, these figures must be used with some caution, as there is some risk of misinterpretation.“ The authors also note that a number of efforts were underway to collect superior data on a more consistent and widespread basis.

There is also an interesting table, Table 5.1, on page 5-12. This table presents the emergency maintenance costs for various components. The components are overhead lines, underground unducted cables, underground ducted cables, underground dig-in on concrete duct bank, polemount switch, pad-mount switch, submersible switch, polemount transformer, pad-mount transformer, submersible transformer, and load break elbow.

The report also provides an extensive bibliography of data sources.

This entire report is documented in detail in an electronic file as part of the documentation for Reliability of Electric Utility Distribution Systems: EPRI White Paper 1000424. The electronic document title is Guide to Reliability Planning notes.doc."

Search terms and ID: System, Data, Financial, Report, 220

Goldberg, 1987

Goldberg, S.; Norton, W.F.; Rose, V.

"Analysis of Feeder Service Reliability Using Component Failure Rates," IEEE Transactions Power Deliver, 1987, October, PWRD-2, 4, 1292-1296, IEEE

A computer based method for analysis of electric distribution feeder reliability is developed. The method utilizes component failure rates and feeder configuration in determining values for the reliability measures: Feeder Average Interruption Frequency Index, (FAIFI) and Feeder Average Interruption Duration Index, (FAIDI). The analysis method is applied to the prediction of the reliability of a Pacific Gas and Electric Company feeder. This 21 kV underground feeder, designated Stockdale 2114, was upgraded extensively during 1985. The effect on reliability of each stage of the upgrade program is evaluated and the cumulative effects on the reliability indices are predicted.

The report presents some component failure data. The data source is not documented. The report is based on a PG&E analysis, so PG&E may be the data source. On page 1295 failure data is provided for switches, distribution transformers, elbows, 10-year-old HMWPE cable, new XLPE cable, old splices, and new splices. Response time is provided in the absence of fault indicators and protection by fusing, with fault indicators but no protection by fusing, with fault indicators and protection by fusing. Repair times are provided for switches, cables, splices, elbows, and transformers.

Search terms and ID: Multiple, Technical, Data, Journal Article, 246

Gonen, 1986

Gonen, Turan

"ELECTRIC POWER DISTRIBUTION SYSTEM ENGINEERING," 1986, McGraw-Hill, New York, New York

This book is totally devoted to power distribution engineering. The author's intention was to fill a vacuum by creating a textbook focused on distribution. This book evolved from the content of courses given by the author at the University of Missouri at Columbia, the University of Oklahoma, and Florida International University. It was written for senior-level undergraduate and beginning-level graduate students, as well as practicing engineers in the electric power utility industry. The book includes topics on distribution system planning, load characteristics, application of distribution transformers, design of subtransmission lines, distribution substations, primary systems, and secondary systems; voltage-drop and power-loss calculations; application of capacitors; harmonics on distribution systems; voltage regulation; and distribution system protection and reliability. This book has been particularly written for students or practicing engineers who may want to teach themselves. Each new term is clearly defined when it is first introduced; also a glossary has been provided. Basic material has been explained carefully and in detail with numerous examples. Special features of the book include ample numerical examples and problems designed to use the information presented in each chapter. A special effort has been made to familiarize the reader with the vocabulary and symbols used by the industry. The addition of the appendixes and other back matter makes the text self-sufficient.

The book provides an extensive chapter on reliability calculations that includes good examples. It only presents one very brief table of failure rates. Table 11-10 page 642 presents normal weather failure rate, average repair time, and disastrous weather failure rate for feeder circuit breaker, distribution transformer, three-phase switch, fuse, and three-phase switch on single-phase lateral. Only the title page, contents, and preface are in the reliability library. The book can be found in the EPRI library.

Search terms and ID: System, Technical, Financial, Book, 271

Guertin, 1976

Guertin, M. B.; Albrecht, P. F.; Bhavaraju, M. P.; Billinton, R.; Jorgensen, G. E.; Karas, A.N.

"List of Transmission and Distribution Components for Use in Outage Reporting and Reliability Calculations," IEEE Transactions on Power Apparatus and Systems, 1976, July/Aug, PAS-95, 4, 1210 - 1215, IEEE

This paper identifies composite systems for which reliability calculations are performed and major components of transmission and distribution equipment for which outage data are recorded. Descriptions such as design and operating characteristics, type, application, etc. which can be used to classify or group components in analyzing outage data are also suggested. The important requirements of an outage reporting procedure are discussed in this report. The information in this paper can be used as a guide by the utility industry in setting up a standard transmission and distribution equipment data bank.

While the paper provides a useful initial step, it needs much additional detail to assure that the data collected are useful for studies of aging component failure and for application within models aimed at optimization of maintenance and replacement decisions and recognizing uncertainty in component performance. No reliability data is reported.

Search terms and ID: Multiple, Other, Journal, 258

Guertin, 1975

Guertin, M. B.; Albrecht, P. F.; Bhavaraju, M. P.; Billinton, R.; Karas, A. N.; Masters, W. D.

"Definitions of Customer and Load Reliability Indices for Evaluating Electric Power System Performance," IEEE Power Engineering Society Conference Papers from the Summer Meeting 75 CH1034-8-PWR, A 75 588-4, 1975, July 20-25, 1-5, IEEE

Paper aims to create uniformity in reporting load interruptions. Four indices are discussed: 1) customer interruption frequency; 2) connected load interruption and curtailment; 3) interruption duration; and 4) service indices.

Table I displays system data for reliability index calculations by presenting bus, number of customers served by feeders from bus and connected load data. Several additional tables display customers interrupted, load interrupted, duration and KVA minute data. Causes of interruptions are not discussed.

Search terms and ID: System, Data, Journal Article, 100

Gunderson, 1992

Gunderson, R.O.; Bhavaraju, M.P.; Billinton, R.; Klempel, D.; Klopp, M.A.; Lauby, M.G.

"Current Industry Practices in Bulk Transmission Outage Data Collection and Analysis," IEEE Transactions on Power Systems, 1992, February, 7, 158-166., IEEE

This paper focuses on the state-of-the-art of bulk transmission outage data collection and analysis. Included in this discussion is the motivation for interest in single and multiple outage event analysis, and identification of where to obtain data on weather conditions which impact the performance of bulk transmission.

Search terms and ID: Non-specific, Monitoring, Journal Article, 249

Gururaj, 1984

Gururaj, B.I.

"Overvoltages and disturbances in power distribution networks," Electrical India, 1984, November 30, 6-C-6-F

"The paper provides a survey of major trends and outstanding issues related to overvoltage and disturbances in power distribution networks. Overvoltages are classified according to duration as transient and temporary overvoltages. If caused by a specific switching operation, they are termed switching overvoltage and if caused by lightning, they are termed lightning overvoltages. The paper classifies voltage dips and fluctuations in voltage as disturbances.

In brief the paper reviews causes, existing solutions, and areas for further development as related to lightning overvoltages, switching overvoltages, characteristics of overvoltages on low voltage networks, voltage dips and fluctuations, and harmonic distortion in power distribution networks. Lastly, the paper states that rapid advances in electronic techniques have substantially increased the capabilities of instruments for use in this area; such as harmonic analysis using μP based instrumentation. The paper also provides references for further studies in each one of the discussed topics. This is an empirical study and does not suggest appropriate models or analysis methods.

Search terms and ID: Multiple, Causes, Design, Journal Article, 202

Hale, 2000

Hale, P.S., Jr.; Arno, R.G.

"Survey of reliability and availability information for power distribution, power generation, and HVAC components for commercial, industrial, and utility installations," 2000 IEEE Industrial and Commercial Power Systems, 2000, 31-54, IEEE, Piscataway, NJ

This paper presents the culmination of a 24000 man-hour effort to collect operational and maintenance data on 204 power generation, power distribution and HVAC items, including gas turbine generators, diesel engine generators, electrical switchgear, cables, circuit breakers, boilers, piping, valves, pumps, motors and chillers. The data collection process and the resultant data are the subject of this paper. The primary purpose of the data collection effort was to provide more current equipment reliability and availability data when performing a facility reliability/availability assessment. Information was obtained on a variety of commercial and industrial facility types with varying degrees of maintenance quality. Data collection guidelines and goals were established to ensure that sufficient operational and maintenance data were collected for statistically valid analysis. A database system, with flexible output capabilities, was developed to track both the equipment information and the contact information. The levels of data quality and maintenance quality were assessed during the analysis phase of the project. The results indicated that the maintenance quality level was a major predictor of equipment

availability; therefore, the availability values presented represent an average maintenance program across all the data sources. In addition, the information obtained can aid facility designers and engineers in evaluating different designs to minimize production/mission failure and to estimate the down times associated with various systems or sub-systems.

"Data was collected as part of the U.S. Army Corps of Engineer's Power Reliability Enhancement Program. The data is stored in the PREPIS (Power Reliability Enhancement Program Information System) database. This is a Microsoft Access database that is available on CD. Equipment age information is included in the database, but not in the printed summary included in this document.

Data was collected for 204 components including HVAC and generation components that are not of interest to this distribution study. The focus was on equipment installed after 1971. For each component a minimum of 3.5 million calendar hours, a minimum of 40 sample components, and a minimum of 5 years of operation were required to develop the data.

The following data is provided about each component in this summary: reliability, inherent reliability, operational availability, unit years, failures, failures/year, mean time between failures, mean time to repair, mean time to maintain, mean down time, mean time between maintenance, and hours downtime per year. These data are further defined below.

These definitions are referenced in several reliability publications and the formulas can be verified in the RAC Toolkit for commercial practices, page 12, or MIL-STD-339, or in the IEEE standard definition publication. Definitions include the following:

(MDI) - Mean Down Time is the average down time caused by scheduled and unscheduled maintenance, including any logistics time.

(MTBM) - Mean Time Between Maintenance is the average time between scheduled and unscheduled maintenance, including logistics time.

(Tp) - Total Period is the Calendar time over which data for the item was collected.

(Rdt) - Repair Down line is the total Down Time for Repairs Due to failures (Unscheduled Maintenance).

(Mdt) - Maintenance Down Time is the Total Down Time for scheduled maintenance (including logistics time).

8760 - Total Hours in a Year (non-leap year).

Ao - Operational Availability considers down time for Scheduled (repair due to failures) and Unscheduled maintenance, including Logistics time. Reference RAC Toolkit. MIL-STD-338, and IEEE Dictionary.

Ai - Inherent Availability considers down time for repair to failures only, no logistics time. Reference RAC Toolkit, MIL-STD-338, and IEEE Dictionary.

Rel - Reliability calculation based on the exponential distribution. Reference RAC Toolkit, MIL-STD-338, and IEEE Dictionary.) lambda represents the failure rate of the item and t represents the period of data collection in calendar time divided by 3760.

Total_Fails - Total number of failure occurrences during the Total Period.

Total_Maint - Total number of maintenance actions (Scheduled Maintenance) during the Total Period.

MTBF - Mean Time Between Failures is the average time calculated between failure occurrences.

MTTR - Mean Time To Repair is the average time to accomplish repairs on an item

MTTM - Mean Time To Maintain is the average time to accomplish maintenance on an item

Hrdt/Yr. - (Mean Hours Down Time per Year) - Average hours the item is expected to be not functional based on a year.

Items with 0 failures, reliability statistics are calculated using the Chi Squared 60% confidence interval based on time truncated data. This common approach to data with no failures associated with the data collection time frame is explained in MIL-HDBK-338, section 8.3.2.5.2, Confidence Limits - Exponential Distribution. These items are identified by an asterisk (*) in the database report.

In the list below the calculated data name is followed by the formula.

Ao, Operational Availability -- Ao = (MTBM/MTBM+MDT)

Ai, Inherent Availability -- Ai = (MTBF/MTBF+MTTR)

Rel, Reliability -- Rel = exp(-(lambda)t)

FR, Failure Rate (per Year) -- FR/Yr. = Total Failures/Tp/8760)

MTBF, Mean Time Between Failures -- MTBF = Tp/Total_Fails

MTTR, Mean Time To Repair -- MTTR = Rdt/Total_Fails

MTTM. Mean Time To Maintain -- MTTM = Mdt/Total_Maint

MTBM. Mean Time Between Maintenance -- MTBM = Tp/All Actions, Maintenance and Repair

MDT. Mean Down Time -- MDT= (Rdt + Mdt)/All Actions, Maintenance and Repair

Hours Downtime per Year -- Hrdt/Yr. = (rpt_repair_time + rpt_maint_time)/(Tp/8760)

The following components are covered by the summary:

Arrester, lightning; battery, gel cell-sealed, system; battery, lead acid, system; battery, nickel-cadmium; bus duct, all types; cable, above ground, in conduit, < 600V; cable, above ground, in conduit, > 600V, <5kV; cable, above ground, no conduit, < 600V; cable, above ground, no conduit, > 600V, <5kV; cable, above ground, trays, < 600V; cable, above ground, trays, > 600V, <5kV; cable, aerial, <15kV; cable, aerial, >15kV; cable, below ground, duct, <600V; cable, below ground, duct, >600V, <5kV; cable, below ground, in conduit, <600V; cable, below ground, in conduit, >600V, <5kV; cable, below ground, insulated, <600V; cable, below ground, insulated, >600V, <5kV; cable, insulated, DC; cable connection, capacitor bank, power factor, corrector; circuit breaker, 600V, 3 Phase, fixed, inducting molded case, <600 amp, normally closed, Trp. Ckt. Incl.; circuit breaker, 600V, 3 Phase, fixed, inducting molded case, <600 amp, normally open, Trp. Ckt. Incl.; circuit breaker, 600V, 3 Phase, fixed, inducting molded case, <600 amp, normally closed, Trp. Ckt. Incl.; circuit breaker, 600V, 3 Phase, fixed, inducting molded case, >600 amp, normally closed, Trp. Ckt. Incl.; circuit breaker, 600V, 3 Phase, fixed, inducting molded case, >600V, <5kV; circuit breaker, 600V, Drawout (Metal Clad), <600 amp, normally closed, Trp. Ckt. Incl.; circuit breaker, 600V, Drawout (Metal Clad), <600 amp, normally open, Trp. Ckt. Incl.; circuit breaker, 600V, Drawout (Metal Clad), >600 amp, normally closed, Trp. Ckt. Incl.; circuit breaker, 600V, Drawout (Metal Clad), >600 amp, normally open, Trp. Ckt. Incl.; circuit breaker, 5kV, Vaccuum, <600 amp, normally closed, Trp. Ckt. Incl.; circuit breaker, 5kV, Vacuum, <600 amp, normally open, Trp. Ckt. Incl.; circuit breaker, 5kV, Vacuum, >600 amp, normally closed, Trp. Ckt. Incl.; circuit breaker, 5kV, Vacuum, >600 amp, normally open, Trp. Ckt. Incl.; Control Panel, Switchgear controls; fuse, >5kV, < 15kV; fuse, 0-5kV; inverters, all types; meter, electric; rectifiers, all types; switch, automatic transfer, > 600 amp, < 600 volt; switch, automatic transfer, 0-600 amp, < 600 volt; Switch, disconnect, enclosed, <600V; Switch, disconnect, enclosed, >5kV; Switch, disconnect, enclosed, >600V, <5kV; switch, disconnect, fused, DC, >600 amp, < 600V, switch, disconnect, fused, DC, 0-600 amp, < 600V, switch, electric, on/off breaker type, non-knife, < 600V; switch, float, electric; switch, manual transfer, < 600amp, < 600V, switch, manual transfer, >600amp, < 600V; switch, oil filled, >5kV; switch, static, >1000amp, <600V; switch, static, >600 amp, <1000amp, <600 V; switch, static, 0-600 amp, <600V; switchgear, bare bus, <600V, all cabinets, Ckt. Bkrs. Not included; switchgear, bare bus, >5kV, all cabinets, Ckt. Bkrs. Not included; switchgear, bare bus, >600V, <5kV, all cabinets, Ckt. Bkrs. Not included; switchgear, insulated bus, <600V, all cabinets, Ckt. Bkrs. Not included; switchgear, insulated bus, >5kV, all cabinets, Ckt. Bkrs. Not included; switchgear, insulated bus, >600V, <5kV, all cabinets, Ckt. Bkrs. Not included; transformer, dry, air cooled, <500kVA; transformer, dry, air cooled, >1500kVA, <3300kVA; transformer, dry, air cooled, >500kVA, <1500kVA; transformer, dry, isolation, Delta Wye, <500kVA; transformer, liquid, forced air, <10,000kVA; transformer, liquid, forced air, <5,000kVA; transformer, liquid, forced air, >10,000kVA, <50,000kVA; transformer, liquid, non-forced air, <3000kVA; transformer, liquid, non-forced air, >10,000kVA, <50,000kVA; transformer, liquid, non-forced air, >3000kVA, <10,000kVA; UPS, rotary; UPS, small computer room floor; Voltage Regulator, static

Search terms and ID: Multiple, Data, Proceedings, 230

Hamman, 1995

Hamman, J.

“Experience with the Use of RCM in a Transmission Maintenance Environment,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 192-197, IEE, Norwich, United Kingdom

Reliability Centered Maintenance (RCM) moves beyond time-based maintenance to take the level of usage and condition of equipment into account. This paper provides a summary of RCM as applied to two pilot programs. RCM stands to be an important training tool because so many disparate parties are involved, each sharing knowledge.

Search terms and ID: System, Technical, Proceedings, 77

Harness, 2000

Harness, R.E.

“Steel distribution poles and their environmental implications,” Industry Applications, 2000, May/June, 6, 3, 53-56, IEEE

Utilities increasingly employ steel distribution poles in their new low-voltage construction partially because steel offers certain environmental advantages over wood. First, steel poles are not susceptible to woodpecker damage. In some regions of the US, woodpecker damage is the most significant cause of wood pole deterioration. Second, steel poles are harder for animals such as eastern fox squirrels (Scirius niger), raccoons (Procyon lotor), and opossums (Didelphis marsupialis) to climb. Keeping animals off utility structures can help reduce outages. Although steel can rust, it is not susceptible to fungal, bacterial, and insect damage. Finally, steel is recyclable.

Contains no useful data. Discusses the electrocution dangers that steel utility poles pose for raptors and other birds. Search terms and ID: Poles, Other, Journal Article, 233

Hartwrigh, 1995

Hartwrigh, R.; Coffey, J.

“Improvement of Customer Service by System Automation, The,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 127-132, IEE, Norwich, UK

Paper discusses improving power delivery standards through system automation.

The paper itself has little to do with reliability of aging assets, but Figure 1 displays the customer minutes lost due to faults at various voltage levels.

Search terms and ID: System, Data, Proceedings, 70

Heising, 1974

Heising, C. R.

"Reliability of Electric Power Transmission and Distribution Equipment," Twenty-Eighth Annual Technical Conference Transactions of the American Society for Quality Control, 1974, May, 314-319

Notes a need for reliability analysis of transmission and distribution system based upon economics. The results would be a guide to both utilities making decisions about system design and maintenance and for manufacturers making decisions about design and cost. After introducing the topic, the author describes analyses from Sweden and France that make use of the failure rates, repair times, and the value of undelivered energy to calculate the value of more reliable equipment. The following sections discuss the availability of data in the US, the importance of estimates of outage times, and failure modes of circuit breakers.

The paper includes a summary of the data from "Report on Reliability Survey of Industrial Plants, Part 1 - Reliability of Electrical Equipment," 1973. This data appears in a Table on page 317. The Table provides Failure rate, industry average downtime per failure, and median plant average downtime per failure for the following items: ELECTRIC UTILITY POWER SUPPLIES Single Circuit; TRANSFORMERS, Liquid Filled-All, 601 - 15,000 Volts, Above 15,000 Volts, Dry Type; 0 - 15,000 Volts, Rectifier; Above 600 Volts; CIRCUIT BREAKERS, Fixed Type (inlc. molded case) All, 0 - 600 volts, Above 600 Volts, Metalclad Drawout - All, 0 - 600 Volts, Above 600 Volts; MOTOR STARTERS, Contact Type; 0 - 600 Volts, Contact Type; 601 - 15,000 Volts; MOTORS, Induction; 0 - 600 Volts, Induction; 601 - 15,000 Volts, Synchronous; 0 - 600 Volts, Synchronous; 601 - 15,000 Volts, Direct Current – All; GENERATORS, Steam Turbine Driven, Gas Turbine Driven; DISCONNECT SWITCHES, Enclosed; SWITCHGEAR BUS, Insulated; 601 - 15,000 Volts, Bare; 0 - 600 Volts, Bare; 601 - 15,000 Volts; BUS DUCT (Unit = One Circuit Foot), All Voltages; OPEN WIRE (Unit 1,000 Circuit Feet), 0 - 15,000 Volts, Above 15,000 Volts; CABLE (Unit 1,000 Circuit Feet), Above Ground & Aerial, 0-600 Volts, 601 - 15,000 Volts - All, In Trays Above Ground, In Conduit Above Ground, Aerial Cable, Below Ground & Direct Burial, 0-600 Volts, 601 - 15,000 Volts - All, In Duct or Conduit Below Ground, Above 15,000 Volts.

Search terms and ID: Multiple, Data, Financial, Proceedings, 255

Henry, 1988

Henry, George E.

“Method for Economic Evaluation of Field Failures such as Low-Voltage Side Lightning Surge Failure of Distribution Transformers, A,” IEEE Transactions on Power Delivery, 1988, April, 3, 2, 813-818, IEEE

A statistical model using life-cycle costing techniques is presented to estimate failure costs of transformers. The model is reliant on an assumed uniform annual failure rate.

Equations involved in the statistical model are presented. No failure data is presented. Discussions regarding the author's model are included. Both discussion summaries point out faults created by the simplicity of the model.

Search terms and ID: Transformers, Financial, Model, Journal Article, 107

Horton, 1991(1)

Horton, William F.; Goldberg, Saul

“Determination of Failure Rates of Underground Distribution System Components From Historical Data,” Proceedings of the 1991 IEEE/PES Transmission and Distribution Conference & Exposition, 1991, September 22-27, 719-723, IEEE

Failure rates for unjacketed cable, transformers and load break rubber elbows are computed from historical data. Such calculations can be made if the data is complete (i.e. contains records of first installation and the number of failures during each year of the record).

"The historical data are from San Diego Gas and Electric Company and the Northwest Electric Light and Power Association (NELPA). NELPA is composed of seven northwestern utilities. The data cover over 20 years of service experience.

Table 1 refers to 24 years of experience and 3800 miles of SDG&E data for HMWPE 15 kV unjacketed cable. The failure rate is given by: $f(t)=0.65t^{0.3}$. Table 1 rows are years (1963-1987) and columns are cumulative miles of cable, miles of cable installed, annual failures, cumulative failures, and calculated cumulative failures. The data is plotted in Figure 1.

Table 2 refers to 20 years of experience and 5800 miles of NELPA data for XLPE 15 kV 175 mil unjacketed cable. The failure rate is given by: $f(t)=0.65$. Table 2 rows are years (1968-1988) and columns are cumulative miles of cable; miles of cable installed, annual failures, cumulative failures, and calculated cumulative failures. The data is plotted in Figure 2.

Similar calculations for 18 years of experience and 2900 miles of NELPA data for XLPE 15 kV 220 mil unjacketed cable. The failure rate is given by: $f(t)=0.13$.

Table 3 refers to 20 years of experience and over 88,000 single-phase pad mounted transformers at NELPA utilities. The failure rate is given by: f(t)=(3X10^-3)t. Table 3 rows are years (1968-1988) and columns are cumulative units, units installed, annual failures, cumulative failures, and calculated cumulative failures. The data is plotted in Figure 3

Table 4 refers to 20 years of experience and over 364,000 load break rubber elbows at NELPA utilities. The failure rate is given by: f(t)=(0.09X10^-3)t. Table 4 rows are years (1968-1988) and columns are cumulative units, units installed, annual failures, cumulative failures, and calculated cumulative failures. The data is plotted in Figure 4 "

Search terms and ID: Multiple, Data, Technical, Proceedings, 41

Horton, 1991(1)

Horton, William F.; Goldberg, Saul; Volkmann, C.A.

“Failure Rates of Overhead Distribution System Components, The,” Proceedings of the Transmission and Distribution Conference, 1991, September, 713-717, IEEE, New York, NY

A 5-year (1984-1989) study of 85 rural and 95 urban non-mountain overhead (OH) distribution feeders in the PG&E system is described. Generic service time failure rates for transformers, switches, fuses, capacitors, reclosers, voltage regulators, and conductor were obtained. The failure rates detailed represent contribution rates to feeder interruptions. The data excludes secondary interruptions so transformer failure rates are relatively lower than might be expected. These failure rates are in reality best estimates of the actual failure rates of the components. A range of deviations about these best estimates can be assessed at various confidence levels. Only transformers were found to exhibit a significant difference in failure rate between rural and urban installations. The component failures contributed about 15% of the total number of sustained outages for the OH feeders of this study. The remaining 85% of the sustained outages were due to external factors (75%) and loss of supply (10%). This suggests that an overhead distribution system is relatively insensitive to component failures, at the existing component failure rate levels.

"Data was from PG&E in the period 1984 to 1989.

Rural data was from 85 feeders with 380 feeder years of data and the following components: 33,686 transformers, 1233 switches, 2491 fuses, 207 capacitors, 149 reclosers, 59 voltage regulators, 7465 mile of conductor.

Urban data was from 95 feeders with 389 feeder years of data and the following components: 18,522 transformers, 1858 switches, 2016 fuses, 338 capacitors, 50 reclosers, 8 voltage regulators, 2439 mile of conductor.

Table 1 presents rural and urban failure rates for each component above."

Search terms and ID: Multiple, Data, Technical, Proceedings, 47

Horton, 1979

Horton, W. F.; St. John, A. N.

"Failure Rate of Polyethylene Insulated Cable, The," 7th IEEE/PES Transmission and Distribution Conference and Exposition, 79CH1399-5-PWR, 1979, April 1-6, 324-328, IEEE

Paper discusses the failure rate of underground polyethylene cables. The authors argue that failure rates should be expressed as a function of the time that the cable is in service. Wide differences in failure data are due to the fact that failures are a function of time and not constant.

The paper begins with an explanation of equations that represent cable failures as a function of time. Table 1 displays 35-kV cable (polyethylene) and crosslinked polyethylene failures as a function of the year installed, the conductor feet installed that year and conductor feet cumulative. Tables 2 and 3 display polyethylene cable and cross-linked polyethylene conductor miles installed, calculated cumulative failures at year-end and reported cumulative failures at year-end. Figures 1 and 2 display reported and calculated cumulative failures at year-end versus time (in years) for PE and XPE cables. Tables 4 and 5 display SDG&E #2 and 4/0 AWG copper 220 mil polyethylene cable conductor miles installed in year, conductor miles removed the same year, calculated cumulative failures at year end and reported cumulative failures at year end. Figures 3 and 4 display reported and calculated cumulative failures at year-end versus time (in years) for SDG&E #2 and 4/0 AWG copper 220-mil polyethylene cable.

Search terms and ID: Cables, Data, Equations, Journal Article, 113

Hoskins, 1999

Hoskins, R.P.; Strbac, G. ; Brint, A.T.

"Modeling the Degradation of Condition Indices," IEEE Proceedings, 1999, July, 146, 4, 386-392, IEE

"The paper observes that the majority of networks are approaching their 35-40 year envisaged lifespan. Most assets have been subject to regular preventive maintenance, which makes failures rare and inference about future lifetimes difficult. The paper argues that in such situations, importance should be given to obtaining condition information to aid asset management. In this connection, some issues that are presently receiving attention are the time schedule and extent of network replacements, the impact on risk and cost in extending the interval of a time-based maintenance policy, and the effect of a particular asset management policy on the future condition of network assets.

Since most structured approaches to formulating asset management decisions require information detailing the condition of the assets, modeling condition information has become a vital component in asset management. The paper both discusses possible data structures such as subjective overall ratings, overall performance indices, and separate component measures, and details of Markov condition modeling after arguing its suitability for condition modeling. Different aspects of Markov models and estimation procedures are discussed and the technique is applied to oil condition modeling of oil-filled switchgear data. The paper further illustrates the impact of such modeling in making better asset management decisions.

The paper does not measure the risk associated with extending the interval of a time-based maintenance policy. The authors do not address what appears to be a fundamental issue: what is the optimal time between maintenance events, and what should be maintained or what is the optimal level of maintenance? Further, the paper does not specifically address the consequences of doing nothing.

The need for a model based on component conditions is advocated. A Markov model describing asset management (AM) decisions based on the deterioration of oil will provide an indication of the deterioration of equipment. Two Markov methods, the maximum likelihood approach and least square approach, are presented. State probabilities, risk of being in a particular state, and probability distribution of time to enter a state can be computed."

Table 5 presents state transition probabilities relating to four states of oil condition in the switches. A Markov process is suggested due to its application to similar problems. Markov models may have to be re-examined after more data becomes available. Case study and appendix on Markov modeling provided.

Search terms and ID: Switches, Technical, Data, Journal Article, 34

Hsu, 1990

Hsu, Y.Y.; Chen, J.L.; Chen, L.M.

“Application of a Microcomputer-Based Database Management System to Distribution System Reliability Evaluation,” IEEE Trans. on Power Delivery, 1990, Jan, 5, 1, 343 - 350, IEEE

The experience with the application of a database management system (DBMS) to handle the large amounts of data involved in distribution system reliability evaluation is reported. To demonstrate the capability of the DBMS in data manipulation, reliability evaluation of a distribution system in Taiwan is performed using a DBMS installed on an IBM PC/AT. It is found that using DBMS tool is a very efficient way of organizing data required by distribution planners. Moreover, the DBMS method is very cost-effective since it is installed on a personal computer.

No component level failure data is presented. Calculated indices such as SAIFI, CAIDI, etc. are provided for individual feeders to illustrate the uses and outputs of the database analysis system.

Search terms and ID: System, Technical, Journal Article, 247

IEEE, 1974(1)

IEEE

"Report on Reliability Survey of Industrial Plants, Part VI: Maintenance Quality of Electrical Equipment, Correction to," IEEE Transactions on Industry Applications, 1974, Sept./Oct., 1A-10, 5, 681, IEEE

Table of population of electrical equipment versus maintenance quality and normal maintenance cycle. Addendum to a paper previously presented in the Journal.

Table 64 presents transformer, circuit breaker, motor starter, motor, generator, and disconnect switch maintenance cycles. Maintenance quality for each component is rated as excellent, fair, poor or none.

Search terms and ID: System, Maintenance, Journal Article, 106

IEEE, 1974(2)

IEEE

"Report on Reliability Survey of Industrial Plants, Part III: Causes and Types of Failures of Electrical Equipment, the Methods of Repair, and the Urgency of Repair," IEEE Transactions on Industry Applications, 1974, March/April, 1A-10, 2, 242-252, IEEE

Paper presents failure types and methods of repair from a reliability survey of 68 industrial plants in the United States and Canada. Specifically presented are failure repair methods; failure repair urgency; failure, months since last maintained; failures, damaged parts; failure type; suspected failure responsibility; failure initiating cause; failure contributing cause; and failure characteristics.

Table 31 displays the number of failures for electric utility power supplies by type. Table 32 displays the number of failures for each main equipment class. Tables 33 through 41 display failure repair methods, failure repair urgency, months between failures and last maintenance, damaged parts, failure types, suspected failure responsibilities, failure initiating causes, failure contributing causes, and failure characteristics for electric power supplies, transformers, circuit breakers, motor starters, motors, generators, disconnect switches, switchgear bus - bare, bus ducts, open wires, cables, cable joints, and cable terminations. Table 42 displays simultaneous failures of all circuits in electric utility suppliers. Table B displays failures as a function of preventative maintenance and time. An unlabeled table displays the percentage of electric power distribution components culpable for system failures.

Search terms and ID: System, Causes, Data, Journal Article, 109

IEEE, 1974(3)

IEEE

"Report on Reliability Survey of Industrial Plants, Part IV: Additional Detailed Tabulation of Some Data Previously Reported in the First Three Parts," IEEE Transactions on Industry Applications, 1974, July/August, 1A-10, 4, 456-462, IEEE

Paper presents data from a reliability survey of 68 industrial plants in the United States and Canada.

Table 43 presents failure modes of metal clad drawout and fixed type circuit breakers for varying voltages. Tables 44 and 45 present cost of power outage data. Tables 48 to 50 present the data regarding the effect of failure repair methods and failure repair urgency for liquid-filled transformers, metal clad drawout circuit breakers, motors and cables for various voltages. Tables 51 through 56 present data regarding downtime due to failures.

Search terms and ID: System, Data, Causes, Journal Article, 110

IEEE, 1974(4)

IEEE

"Report on Reliability Survey of Industrial Plants, Part V: Plant Climate, Atmosphere, and Operating Schedule, the Average Age of Electrical Equipment, Percent Production Lost, and the Method of Restoring Electrical Service after a Failure," IEEE Transactions on Industry Applications, 1974, July/August, 1A-10, 4, 463-466, IEEE

Paper presents climate, atmosphere, age, operating schedule, etc. data from a reliability survey of 68 industrial plants in the United States and Canada.

Table 58 presents percent production lost and total failures reported for transformers, circuit breakers, motor starters, motors, generators, disconnect switches, switchgear bus - bare, bust ducts, open wires, cables, cable joints, and cable terminations. Table 60 presents the average age of electrical equipment reported for transformers, circuit breakers, motor starters, motors, generators, disconnect switches, switchgear bus - bare, bus ducts, open wires, cables, cable joints, and cable terminations.

Search terms and ID: System, Data, Causes, Journal Article, 111

IEEE, 1974(5)

IEEE

"Report on Reliability Survey of Industrial Plants, Part VI: Maintenance Quality of Electrical Equipment," IEEE Transactions on Industry Applications, 1974, July/August, 1A-10, 4, 456-462, IEEE

Paper presents maintenance quality, schedule maintenance and failure due to inadequate maintenance data from a reliability survey of 68 industrial plants in the United States and Canada.

Table 64 presents switchgear bus (insulated and bare), open wire, cable, cable joints and cable termination maintenance cycles. Maintenance quality for each component is rated as excellent, fair, poor or none. Tables 65 and 66 present maintenance quality and maintenance cycle time for transformers, circuit breakers, motor starters, motors, generators, disconnect switches, switchgear bus - bare, bust ducts, open wires, cables, cable joints, and cable terminations. Tables 67 through 78 displays the number of transformer, circuit breaker, motor starter, motor, generator, disconnect switch, switchgear bus - bare, bus duct, open wire, cable, cable joint, and cable termination failures versus the number of months since maintained and maintenance quality. Tables 79 and 80 present the number of failures versus maintenance quality and months since maintained for all equipment classes combined.

Search terms and ID: System, Data, Causes, Journal Article, 112

IEEE, 1974(6)

IEEE

"Report on Reliability Survey of Industrial Plants, Part I: Reliability of Electrical Equipment," IEEE Transactions on Industry Applications, 1974, March/April, IA-10, 2, 213-235, IEEE

Paper presents reliability data from a reliability survey of 68 industrial plants in the United States and Canada.

Several equations used in the statistical analysis of equipment failure data are presented. Figure 1 presents failure rate confidence levels for the collected data. Table 2 presents equipment failure rate and equipment outage duration data. Included in Table 2 are failure rate, downtime per failure and average estimated clock hour to fix failures data for electric utility power supplies; transformers; circuit breakers; motor starters; motors; generators; disconnect switches; switchgear buses; bus ducts, open wires; cables; cable joints; cable terminations and other miscellaneous components. Tables 3 through 18 present sample size, number of failure, industry, equipment, failure rate and actual downtime data for electric utility power supplies; transformers; circuit breakers; motor starters; motors; generators; disconnect switches;

switchgear buses; bus ducts, open wires; cables; cable joints; cable terminations and miscellaneous equipment. Appendix A contains a copy of the survey used to obtain the data.

Search terms and ID: System, Data, Causes, Journal Article, 119

IEEE, 1968

IEEE

"Proposed Definitions of Terms for Reporting and Analyzing Outages of Electrical Transmission and Distribution Facilities and Interruptions," IEEE Transactions on Power Apparatus and Systems, 1968, May/June, PAS-87, 5, 1318-1323, IEEE

Paper presents suggested definitions for describing outages of transmission and distribution facilities and interruptions to customers. Discussions are presented arguing the merits of the proposed definitions.

No real data is presented. Proposed definitions are divided into three groups: General Terms, Outage Terms, and Interruption Terms.

Search terms and ID: System, Data, Journal Article, 116

IEEE/PES Task Force on Impact of Maintenance Strat., 1999

IEEE/PES Task Force on Impact of Maintenance Strat.

"Impact of Maintenance Strategy on Reliability," 1999, July, IEEE

The agenda of the report is to educate the electrical industry about reliability-centered maintenance (RCM). The paper describes deterministic and probabilistic models to determine maintenance policies. The report covers in great detail definitions of ageing, failures, deterioration, repair and maintenance, etc., and the classification of failures. Ageing and maintenance

Although no specific data are presented, ageing and maintenance are covered in depth, including definitions of failures and the stages of deterioration. Deterioration is delineated by two definitions: deterioration by way of duration or physical signs (corrosion, wear, etc.). Of particular interest are the inclusion of simple state diagrams for mathematical models based on ageing failures for differing maintenance schedules and state diagrams for random and deterioration failures. The report states that probabilistic models for reliability are superior but recognizes that models (probabilistic or otherwise) are rarely used. The report also highlights that maintenance is done particularly during times when energy prices are low, and thus when

it's more economically feasible. The survey questions the researchers used to generate data on maintenance policies were included.

Search terms and ID: Multiple, Maintenance, Monitoring, Report, 17

Jones, 1987

Jones, T.L.; Kogan, V.I.

"Application of operations research to the failure associated problems of URD cables," 14th Inter-RAM: International Reliability, Availability, Maintainability Conference for the Electric Power Industry, 1987, 282-9, Pennsylvania Power & Light Co, Wescoville, PA

The failure data of a subsample of 15 kV URD cables on the AEP System are analyzed to establish their optimum economic life. The nonhomogeneous Poisson process was adapted as the failure model for repairable URD cables. The Gompertz distribution was favorably compared to the Weibull as the applicable failure distribution. Three different repair-replacement policies were considered and applied with results compared to each other. A sensitivity study for Policy III was incorporated and practical recommendations were made. The whole study is based upon the operations research approach and is of a very general nature with wide applicability to optimal repair-replacement decisions.

"AEP data from Indiana mostly of high molecular weight polyethylene insulated cables. Assumed homogeneous cables and similar stresses. Figure 1 plots year versus miles of cable and year versus failures for 1969 to 1985. Figure 2 compares the number of miles installed in each year to the number of failures experienced by each vintage. Table 1 reports age, number of units, reported failures, number of new units, units replaced, and adjusted number of failures. Using these data maximum likelihood estimates of the parameters of Weibull and Makeham-Gompertz distributions for the failures are estimated. These parameter values are provided in the paper. These estimates were highly unstable depending on the starting point for the numerical solution. The authors also solved for parameters using a modified method-of-moments procedure. These parameter estimates were more stable.

The parameter fitting approach may also be of interest."

Search terms and ID: Cables, Technical, Data, Proceedings, 238

Kariuki, 1995

Kariuki, K.K.; Allan, R.N.

"Reliability Worth In Distribution Plant Replacement Programmes," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 162-167, IEE, Norwich, UK

Paper challenges the notion that replacement should be based solely cost-benefit analyses, and suggests that technical criteria such as reliability be considered. Models show that the Incremental System Customer Outage Costs should be considered as part of cost-benefit analyses when determining the replacement of distribution system components.

Model-generated data is presented. Table 2 summarizes the qualitative effects of asset replacement in terms in the changes in average failure rate, average outage duration and number of customers affected. Table 4 displays model-generated replacement scenarios and delta SCOC.

Search terms and ID: System, Financial, Technical, Proceedings, 74

Kelley, 1999

Kelley, Arthur; Edwards, Steven; Rhode, J.P.; Baran, M.E.

"Transformer Derating for Harmonic Currents: A Wide Band Measurement Approach for Energized Transformers," IEEE Transactions on Industry Applications, 0093-9994, 1999, Nov/Dec, 35, 6, 1450-1457, IEEE

A review of IEEE Recommended Practice C57.110 regarding the derating of transformers using calculations based on dc winding resistance and rated load loss. The authors present an alternative method to C57.110 based on direct measurement performed at fundamental and harmonic frequencies that can be performed whether or not the transformer is energized and in service.

Paper discusses transformer derating in detail and presents several equations regarding eddy-current loss, etc., used in the derating process. Data from a finite element test model is presented. The data for both primary and secondary winding include number of turns, number of layers, turns per layer, wire gauge, effective conductor thickness, window height, length of winding turn, and dc winding resistance. Test result data for the FEA model also include magnetic field and current density for dc and 8 kHz. Graphs are also presented for effective ac resistance versus frequency and effective ac inductance versus frequency. Table II displays the distribution transformer data of primary and secondary transformer resistance for 10, 50 and 100 kVA transformers. Table III displays measured resistances at harmonic frequencies for 10, 50 and 100 kVA transformers.

Search terms and ID: Transformers, Causes, Technical, Journal Article, 87

Kogan, 1996

Kogan, V. I.; Roeger, C. J.; Tipton, D. E.

“Substation Distribution Transformers Failures and Spares,” IEEE Transactions on Power Systems, 1996, November, 11, 4, 1905-1912, IEEE

"Electric utilities should have a sufficient number of spare transformers to backup substation distribution transformers to replace transformers that fail and require factory rebuild or replacement. To identify such a number, the statistical methodology was developed to analyze available failure data for different groups of transformer. That methodology enables the estimation of future numbers of failures with associated probabilities, recommends the proper number of spares, identifies the necessity and shows the means to shorten the transformer's replacement time.

Paper discusses the use of homogeneous Poisson process (HPP) statistical methods to analyze transformer failure data in order to determine a sufficient number of spare transformers necessary to keep systems running in the event of a failure. "

Equations behind the HPP methodology are presented. Data from example calculations is presented. Tables 1.1, 1.2, 8 and 10 display factory repairable or scrap failures and exposure risk for a group of 69 13 kV transformers. Other tables display probabilities of expected failures for experimental data.

Search terms and ID: Transformers, Technical, Equations, Journal Article, 98

Kogan, 1994

Kogan, V. I.; Jones, T. L.

“Explanation for the Decline in URD Cable Failures and Associated Nonhomogeneous Poisson Process, An,” IEEE Transactions on Power Delivery, 1994, January, 9, 1, 534-543, IEEE

The possible need to remove from service approximately 2000 miles of high molecular weight polyethylene URD cable has been a topic of concern at American Electric Power. Earlier projections indicated that failures would increase at an exponential rate and that a typical section of cable would be replaced prior to reaching 30 years of age. However, data analysis shows a downward trend in failures after a cable system has been operating for about 18 years. A possible explanation for this finding is the elimination of cable defects through the failure repair (splicing) process. The authors' findings suggest that, in addition to age and failure history, the decision to remove a cable section from service should be based on the condition of the cable after repair.

Tables I and II display the number of 15 kV HMW URD cable failures and number of cable runs removed from service by the year if installation for the Roanoke Division (1984-1991) and St. Joseph Division (1972-1991). Table III displays the number of cable runs with first repeated failures over life of run and n number of isolating devices with repeated operations over one year period, respectively, by installation year for the Roanoke Division, 1984-1991. Figures 1 and 2 display the expected number of failures on one standard cable run during one year interval by age at failure for the Roanoke Division, 1984-1991 and St. Joseph Division, 1969-1991, respectfully (both show increasing failures to a point of time, and then a decrease in failures). Figures 3 and 4 display the number of reported failures and number of cable runs removed from service by report year for the Roanoke Division, 1984-1991 and St. Joseph Division, 1982-1991, respectfully. Additionally, several equations regarding the nonhomogeneous Poisson process are provided.

Search terms and ID: Cables, Equations, Data, Journal Article, 94

Koglin, 1983

Koglin, H.J.; Roos, E. ; Wellssow, W.H.

"Application of Reliability Calculation Methods to Planning of High Voltage Distribution Networks," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 64-67, IEE, London, United Kingdom

Paper outlines method to calculate reliability indices for substations and to use these indices in the network planning process. The network reliability calculation relies upon data, modeling, methods, and values.

Parameters were estimated by analyzing over 1000 observed outages. No information is provided on the time frame of the outages or the number of components. Contains an input Table for modeling that includes frequency of outages, duration of outages, conditional probabilities for lines, cables, transformers, and busbars. Outages are classified as independent outages, multiple earth faults, missing operation of protection, scheduled outage of reserve components, and multiple line faults.

Search terms and ID: Multiple, Financial, Data, Proceedings, 3

Kostyal, 1982

Kostyal, S.J.; Vismor, T.D.; R. Billinton

"Distribution System Reliability Handbook," EL-2651, 1356-1, 1982, December, EPRI, Palo Alto, California

The objectives of this research project are a compilation and an organization of reliability assessment techniques in use in 1981. A 3-volume final report (see below, EL-2018) documents the research. This practical distribution handbook for EPRI client utilities arose from the project. It describes the assessment models in detail, models for historical reliability assessment

(HISRAM) and predictive reliability assessment (PRAM), which were successfully tested and executed at two utilities. It also includes practical guidelines for reliability assessment. It contains an extensive bibliography on distribution system reliability evaluation grouped into (a) analysis and applications, (b) outage data, and (c) reliability economics and indices; including abstracts for the most significant articles.

"Provides data only as needed for examples. Page 4-13 provides illustrative failure rates and repair times for mains and laterals. Page 4-23 provides illustrative failure rates and repair times for lines, breakers, transformers, and buses. Page 4-33 provides illustrative failure rates and repair times for lines, breakers, and transformers for both normal and adverse weather.

Contains an extensive reference list of sources of failure data. We will attempt to collect these articles."

Search terms and ID: System, Financial, Technical, Report, 219

Krishnasamy, 1994

Krishnasamy, S.G.; Kulendran, S.

“Reliability analysis of an existing distribution line,” Probabilistic Methods Applied to Power Systems. 4th PMAPS, 1994, September, 435-447, World Energy Council, Rio de Janeiro, Brazil

A method is presented to calculate the reliability of an existing wood pole distribution line. The purpose of this method is to provide the maintenance engineer a tool to identify individual poles, which do not meet the specified reliability requirements. The method calculates the reliability of each individual pole as well as the overall reliability of the line using the actual measured pole strength and other line details.

The outline of the method is sketchy and the presentation of the results is unclear.

Search terms and ID: System, Technical, Proceedings, 270

Kumar, 1996

Kumar, Dhananjay; Westberg, Ulf

“Proportional Hazards Modeling of Time-Dependent Covariates Using Linear Regression: A Case Study,” IEEE Transactions on Reliability, 0018-9529, 1996, September, 45, 3, 386-391, IEEE

Covariates are assumed to be time-dependent in proportional hazard models. The authors present a graphical method based on a linear regression model to determine the validity of that assumption. The slope of the graphical representation can show if the covariate in question is time dependent or not. The linear regression model showed that some covariates were indeed time dependent. The method is suggested as a supplement to proportional hazards models. Covariates include, but are not limited to, operating environments (temperature, dust, pressure, humidity), operating history (overhauls, effect of repairs or preventative maintenance), and types of design or materials used.

Equations are presented to lay the foundations of proportional hazard models and the Aalen Linear Regression Model. Data for the paper is from a mining operation in Sweden. Figure 2 displays the average failure time in hours versus the failure number. Table 1 shows the results of probabilistic hazard models and linear regression models, displaying the covariate, Cox regression coefficient, Cox Model t-statistic and LRM TST. Figure 3 shows the cumulative regression functions versus time for different covariates (cable type, first failure number, and new welded joint). Table 3 displays the results of proportional hazards model, with covariate versus Cox regression coefficient and Cox model t-statistic.

Search terms and ID: Cables, Equations, Technical, Journal Article, 88

Kurunsaari, 1999

Kurunsaari, Sami

"Asset management system built from scratch," Transmission & distribution world, 1999, April, NA

Describes WorkMap, a database system developed by IVO TE of Finland, for describing all components of a distribution and transmission system and tracking maintenance and monitoring activities for the components.

Search terms and ID: System, Monitoring, Maintenance, Journal Article, 214

Lapworth, 1995

Lapworth, J.A.; Jarman, P.N.; Funnell, I.R.

"Condition Assessment Techniques for Large Power Transformers," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 85-90, IEE, Norwich, UK

Paper discusses the monitoring and diagnosis of large power transformers. Methods such as oil analysis, winding movement detection, etc., are discussed. Has a very detailed discussion of tests and their uses.

Paper contains secondary transformer fault data. Figure 1 presents a graph of arcing faults as a function of gas level versus date sampled. Table 2 displays failed transformer low frequency response.

Search terms and ID: Transformers, Monitoring, Proceedings, 69

Lebow, 1998

Lebow, M.A.; Vainberg, M.

“Asset Management Planner,” Proceedings of the American Power Conference, 1998, 1, 435-440

"Asset Management Planner (AMP) is a quantitative probabilistic program that can evaluate optimum lifecycle costs of equipment. It incorporates the purchasing, minor repair costs, major repair costs, and the duration of inspections, repairs and failures. The authors discuss improvements in AMP to incorporate probability densities. Output can be displayed as sensitivity analyses for expected time of failure as a function of time between inspections. The Average Life Repair Cost (ALRC) is also discussed.

The paper describes a computer program based on a probabilistic approach to asset management. The planner can provide input to reliability-centered management (RCM) and other qualitative methodologies. The central premise of the AMP model is that equipment aging can be represented by discrete stages. The model describes the maintenance of a population of equipment and consists of the states the equipment can assume and the transition among them. A Markov process is used for the model and the rates associated with the transitions are assumed constant. Three equipment states are assumed: initial, minor deterioration, major deterioration, and failure. Repair after failure returns the device to the initial stage. In the proposed model, regular inspections are conducted and as a result decisions are made to perform minor maintenance, major maintenance, or do nothing. The inputs to the program are chance probabilities (probability of transition from one state to another) and choice probabilities (probability of making one of the three decisions being in each one of the states) that are either estimated from historical records or supplied by the user.

The tool generates the state probabilities, the shortest mean times the process can move from one state to another, and with further mathematical manipulation, answers such questions as “what is the probability that the device will not fail in the next 6 months, given that it has already reached the third deterioration stage?”

The tool allows study of the effects resulting from changes in several controllable parameters such as frequency of inspections and repair times, and aids establishing optimal policies. The authors report new developments being implemented that allow for calculation of probability distributions of time to failure (rather than the mean values). This enables the decision-makers to study the effect of maintenance policies on, for example, the number of years before failure occurs at some risk level, which can be set as a probability threshold by the user. The authors present an example of the application of the program to 230 kV air blast breakers.

"

Example analysis of 230-kV air-blast breakers with a total operating history of 100 breaker-years. The time period is not specified. Shows transition probabilities among four defined Markov states. Figure 4 shows transition times to inspection interval. Figure 6 shows the cumulative probability function of the remaining life of the breakers in years from the major deterioration state. Figure 7 shows the unavailability of the breaker as a function of the time to inspection in the minor deterioration state. Equipment aging can be represented by discrete stages. Repair after failure returns a device to an "as new" condition.

Search terms and ID: Switches, Technical, Data, Journal Article, 25

Li, 1999

Li, W; Vaahedi, E; Mansour, Y.

“Determining Number and Timing of Substation Spare Transformers Using a Probabilistic Cost Analysis Approach,” IEEE Transactions on Power Delivery, 1999, July, 14, 3, 934-939, IEEE

"Compared to the N-1 security design principle in each substation, common spare transformers shared by multiple substations can avoid considerable capital expenditure and still assure a sufficient reliability level. Using common spare transformers has been already a practice of some electric utilities in distribution substation transformer planning. This paper presents a probabilistic approach to determining the number and timing of spare transformers shared in a substation group. The proposed approach is based on the aging failure model of transformers, the overall reliability analysis and the probabilistic damage cost model for a substation group, and the capital cost model for spares and the present value method. The spare transformer scheme obtained using the presented approach provides both cost efficiency and sufficient reliability. A single transformer substation group in a nonurban region is given as an application example to illustrate the procedure of the method.

Probabilistic approach based on aging failure model, reliability analysis, and probabilistic damage cost model are used to determine the number and timing of spare transformers shared in a substation group. The paper predicts that using probabilistic cost analysis in conjunction to adding spare transformers can be a cost effective way to maintain power to customers."

Data is generated from a 26 single transformer substation group in a non-urban region. Several aging failure model equations are presented, as well as a failure rate function of normal distribution (Figure 1). Table 1 presents substation data, including each individual substation, its in-service year, and its 1998 peak load (MW). Table 2 displays the annual probabilities of the cumulative loss-of-load state for the substation group, including the year, and probabilities for spares 0 through 5. Table 3 displays the savings in damage costs due to adding spares projected for years 1998 through 2017 for the first through fifth spare. Table 4 presents the cash flow for capital investment and damage cost savings projected for years 1998 through 2017, including the capital required and the damage savings predicted.

Search terms and ID: Transformers, Technical, Financial, Journal Article, 92

Light, 1983

Light, B.R.

"Transient Stability Aspects of Power System Reliability (CEGB System)," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September 19-21, 101-104, IEE, London, United Kingdom

Standards for adequate reliability of generation from 400 and 275 kV supergrid networks are discussed. Strategies for designing and operating criteria are presented to ensure that synchronism is maintained under all credible fault conditions. Consequences of stability losses are discussed.

Table 1 presents fault type (single phase to earth, 2 phase, 2 phase to earth, and 3 phase) and rate data are presented for overhead lines, transformers, switchgear, busbars, and cables for 400kV and 275kV systems. Data is from the Central Electricity Generating Board system in the United Kingdom for the 1968 to 1974 period. Data is "to some uncertainty due to incorrect fault diagnosis and/or reporting an also the sampling period considered."

Search terms and ID: Multiple, Data, Technical, Proceedings, 15

Logan, 1994(1)

Logan, D.M.; Billinton, R.

"Value-based transmission resource analysis, Volume 1: technical report," TR-103587-V1, 2878-02, 1994, April, EPRI, Palo Alto, California

Value-based transmission resource analysis (VBRTA) is a comprehensive approach for evaluating the reliability and operating cost impacts of generation and transmission investments and related utility decision on a consistent basis. This report describes a practical framework for implementing VBTRA and demonstrates the framework with a number of case studies. The case studies demonstrate the application of the framework to determining the optimal transfer capability across a particular transmission interface, evaluating specific transmission reinforcements, comparing transmission and generation alternative to serve local area reliability needs, and comparing alternative transmission substation designs. The case studies involve Pacific Gas and Electric Company and Duke Power Company. Chapter 1 provides and introduction. Chapter 2 provides a historical perspective on approaches to this problem. It includes extensive references, 187 citations. Many of these deal with customer outage costs. Chapter 3 describes the VBRTA methodology. It includes descriptions of several software packages that support analyses. Chapter 4 is a case based on the IEEE reliability test system. Chapter 5 presents the utility case studies, and Chapter 6 presents conclusions and recommendations.

In the case studies, a considerable amount of failure data is presented for components. The provenance of the data is not described. The components are transmission level equipment, 115kV and 230kV. Table 5-7 provides data for PG&E. The columns are Contingency, MW unsupplied for 100% load level, Frequency in occurrences per year, and Duration. Tables 5-8 to 5-12 provide the same data for other alternatives. Duke data is provided in Tables 5-19, 5-21, and 5-22.

Search terms and ID: System, Financial, Data, Report, 225

Logan, 1994(2)

Logan, D.M.; Billinton, R.

"Value-based transmission resource analysis, Volume 2:applications guide," TR-103587-V2, 2878-02, 1994, April, EPRI, Palo Alto, California

Value-based transmission resource analysis (VBRTA) is a comprehensive approach for evaluating the reliability and operating cost impacts of generation and transmission investments and related utility decision on a consistent basis. This report describes a practical framework for implementing VBTRA and demonstrates the framework with a number of examples. Chapter 1 summarizes VBTRA principles and approaches. Chapter 2 reviews a number of computer programs that support analysis. Chapter three is the focus of this report and the longest chapter. It provides four brief examples of VBRTA applications including one application to a distribution system.

Search terms and ID: System, Financial, Technical, Report, 226

Longo, 2000

Longo, Vito; Puntel, Walter R.

“Evaluation of Distribution System Enhancements Using Value-Based Reliability Planning Procedures,” IEEE Transactions on Power Systems, 2000, August, 15, 3, 1148-1153, IEEE

Value-Based Reliability Planning (VBRP) methods incorporate relative investment, operating costs and reliability valuation, which includes performance during transformer failures and aging from increased stress on remaining transformers. This paper illustrates the application of value-based reliability planning (VBRP) methods to the problem of distribution substation capacity enhancement. The traditional approach is to consider relative investment and operating costs of various alternatives. VBRP enhances the traditional approach with the addition of reliability valuation. This includes a detailed representation of performance during transformer failures and the accelerated aging from increased stress on remaining transformers, as well as the cost of customer interruptions. The addition of a transformer is compared with various distributed resource options, and also the option of doing nothing and incurring more frequent interruptions and greater stress. This paper illustrates the usefulness of VBRP techniques for the planner who must consider customer value in planning decisions. The paper shows how transformers can be reinforced by diesel, battery and DSM reinforcements, thus reducing the percentage of loss of life.

Data presented is from a "typical" substation, so it is not clear if the data is actual or simulated. The key take-away data from the article is displayed in Figure 2, which shows customer damage functions for firm loads and interruptible loads. The graph plots interruption cost ($/kW) versus interruption duration (hours). Figure 3 displays the percentage of transformer loss of life (percentage versus years) for five cases (base case, 3 transformers, diesel units (MTTR = 85 hours), DSM (MW increments) and batteries (% MW for 3 hours).

Search terms and ID: Transformers, Financial, Causes, Journal Article, 97

Lonsdale, 1983

Lonsdale, J.G.; Hitchen, G.B.

“Reliability Evaluation in the Planning of Distribution Systems,” Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 77-80, IEE, London

This article concentrates on 33/11 kV substations because of the major investments in these systems. Due to the heavy capital investment in substations, systems must be designed to meet precise demand. The authors contend that it is acceptable for automatic load switching at 11kV instead of constructing reinforcing systems. A table is provided that helps assess at which point load switching will be insufficient and system reinforcements will be necessary.

Data is from the National Fault and Interruption Reporting Scheme (NAFIRS). Data table with fault rates for underground cables, overhead lines, transformers, and switchgear. Other tables with calculated data for outage times and corresponding economic consequences.

Search terms and ID: System, Technical, Data, Journal Article, 13

Mackevich, 1990

Mackevich, J.P.; Lynch, D.

“Investigation Into Gas Pressure Generation In New and Aged Aluminum Conductor Cable and the Internal Pressure Withstand Capabilities of Joints, An,” IEEE Transactions on Power Delivery, 1990, April, 5, 2

"Water in the strands of electric power cables has been determined to adversely affect service life. In aluminum conductor cable, there can be additional contribution to failure from gas generated by the water-aluminum reaction. This pressure build-up may be substantial resulting in accessory interfacial breakdown and failure due to pressure venting. As a remedy, the industry is exploring various ways to eliminate water in cable by design changes.

The paper reports experimental results on pressure build-up in new and aged aluminum conductor cables. Tests on new cables show that heat is needed to start the reaction. Cables aged for four months were filled with water and heated with induced current to achieve 70° C. After 24 hours of continuous heating the samples all registered some increase in internal pressure but there was considerable variation in the pressure values. The samples were allowed to cool to ambient temperature and reheated to 90° C. While some samples exhibited higher pressure build-up, some other showed lower pressures. This distribution of data indicates that the impact of variables that contribute to pressure build-up has yet to be fully understood.

The paper also tests three joint technologies for internal pressure-withstand capabilities under load with applied voltage. The authors find that heat-shrink technology exhibits the highest withstand capability. Finally, as a section of cable develops pressure, pressure relief and failure will occur at the point of lowest withstand. Failure and outage time can be minimized if the pressure can be contained or else vented by an accessory with easy access. This is an empirical study and has no modeling value for us."

Heat is required to break down the aluminum oxide for the gas reaction to occur.

Search terms and ID: Cables, Causes, Journal Article, 30

Mariton, 1989

Mariton, M.

“On Systems with Non-Markovian Regime Changes,” IEEE Transactions on Automatic Control, 1989, March, 34, 3, 346-349, IEEE

A non-Markovian model is proposed for use with a jump model because Markovian models exclude systems with rates dependent on the time elapsed since last transition (typically burn-in and aging phenomena).

A lot of equations are presented in a purely theoretical setting.

Search terms and ID: Non-specific, Equations, Journal Article, 86

Marwali, 1999

Marwali, M.K.C.; Shahidehpour, S. M.

"Probabilistic approach to generation maintenance scheduler with network constraints, A," Electrical power & energy systems, 1999, June 11, 21, 533-545, Elsevier

Presents both a quantitative model and a solution procedure for determining an optimal maintenance schedule for generators. The model considers generator outages and network constraints. The solution uses a decomposition approach based on duality theory. Test results demonstrate that the limits on transmission line capacity affect the loading point of units and increase the generation by expensive and inefficient units.

"Generation oriented.

It would be good to scan the abstract and put that in the summary."

Search terms and ID: Generators, Financial, Technical, Journal Article, 58

Marwali, 1998

Marwali, M.K.C.; Shahidehpour, S.M.

"Long-Term Transmission and Generation Maintenance Scheduling with Network, Fuel and Emission Constraints," IEEE Transactions on Power Systems, 1998, August, 1160-1165

The paper presents an integrated long-term scheduler (LTS) for generating companies (GENCO) with local transmission lines and different constraints. The proposed algorithm extends the Benders decomposition to include network, fuel and emission constraints into LTS. The local network is modeled as a probabilistic problem to include the effect of generation and transmission outages. The approach may be summarized as follows. An objective function is introduced as the sum of maintenance cost of generators, maintenance cost of transmission line, energy production cost, and cost of energy purchased outside. The decision variables are sequences over time that respectively give maintenance status of each unit (binary variables), MBtu of each fuel contract allocated to each unit, and purchased energy. A set of constraints is imposed that reflect maintenance constraints, system emission limits, network constraints (modeled as a transportation model), and fuel constraints. The solution methodology is based on the decomposition of the main problem into the maintenance master problem, operation sub-problem, and fuel dispatch problem. A master problem consisting of maintenance and operation sub-problems (a relaxed problem where minimization is only subject to maintenance constraints, emission limits, and network constraints) is first solved using Benders decomposition. The solution to the master problem is based on relaxing the operation sub-problem constraints and adding appropriate cuts from operation constraints. The solution to the master problem is sent to the fuel dispatch problem that solves for purchased energy, calculates fuel cost, and returns this cost to the master problem. This procedure continues iteratively until no further cost improvement is possible and maintenance schedule satisfies all constraints.

No reference to aging assets.

Search terms and ID: System, Financial, Technical, Journal Article, 32

Matulic, 1990

Matulic, D.; Lubkeman, I.

"Decision Support Approach for Considering Reliability Criteria in the Protective Coordination of Distribution Feeders, A," Electric Power Systems Research Journal, 1990, July, 9, 1, 47 - 56, Elsevier Sequoia

This paper describes an approach for incorporating reliability criteria into the design of protective coordination for distribution feeders. This approach introduces a mechanism for considering the impact of momentary interruptions, caused by excessive switching, upon power quality sensitive loads. The development of a decision support tool for implementing this strategy is also presented. This tool aids the protection engineer by selecting appropriate reclosers and fuses from a component database, checking recloser-to-fuse coordination for all device selections and ranking these selections according to user-selected reliability criteria. An example is included to illustrate the concepts described above.

Search terms and ID: Non-specific, Technical, Financial, Journal Article, 250

Matusheski, 1997

Matusheski, Robert L.

"Predicting success," Power engineering, 1997, February, 101, 2, 26

Discusses the state-of-the-art of predictive maintenance (PDM). Reviews real world applications and measuring the success of real programs. Is focused on generation plants.

Search terms and ID: Generators, Monitoring, Maintenance, Journal Article, 213

May, 1987

May, H.S.

"Revitalisation and Renovation of 66 kV Overhead Lines Within N.E.E.B.," International Conference on Revitalising Transmission and Distribution Systems, 1987, February 25, IEE

"The paper discusses revitalization issues. A distinction has been made between revitalization and maintenance as in the latter case the emphasis is on maintaining what is there while in the former case the emphasis is on equipping the asset for a new lease of life. The paper summarizes renovation requirements for single circuit feeders and double circuit feeders, and discusses single circuit redesign. The paper concludes that renovation of existing overhead line routes can be an economic alternative to rebuilding and raises the possibility of affording improvements in both amenity and expected performance without necessarily increasing costs, through concentration upon structural efficiency.

Suggests that older assets were designed more robustly and were able to maintain a high factor of safety over time, allowing for additional economy of renovation."

A table on page 69 provides failure rates for 66kV and 20kV lines as faults/km. There is note that data is from the National Fault reports, but there is no additional information. Summary of renovation requirements is included for several components of distribution equipment. Focus of the article is poles and supports.

Search terms and ID: Poles, Causes, Data, Journal Article, 39

McCoy, 1978

McCoy, M. F.

"Automated Collection of Transmission Outage Data," 1978 Reliability Conference for the Electric Power Industry, 1978, 16-Nov

As part of a project to provide data and models for a system reliability evaluation program, an extensive analysis of the Bonneville Power Administration's outage data collection activity was performed. The major findings are presented in this paper. Particular emphasis was placed on using existing data and procedures to meet the program requirements. The analysis established that the usefulness of an outage data collection scheme is largely determined by the method of describing and coding outages and the ability to calculate the exposure to important failure modes.

This paper describes the BPA system for data collection. It has a history of its development. It includes many of the codes used for recording data and a copy of its failure reporting form. It does not provide data and is oriented to transmission failures.

Search terms and ID: System, Other, Proceedings, 253

McMahon, 1995

McMahon, B.

"Reliability and Maintenance Practices for Australian and New Zealand HV Transmission Line," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 198-203, IEE, Norwich, UK

Survey of reliability-based maintenance for transmission lines. Description of moving maintenance beyond time-based methods to maintenance based on a mixture of inspection types.

End of paper is mission. Figure 1 presents the age of lines as a function of length. Figure 2 presents data based on the form of line construction (wood, concrete, other steel or galvanized steel). Figure 3 displays the type of maintenance patrols (aerial versus ground). Figure 4 displays the life expectancies of structures. Figure 5 life expectancy of conductors. Figure 6 life expectancy of insulators.

Search terms and ID: Multiple, Maintenance, Data, Proceedings, 78

Medek, 1989

Medek, James D.

"Direct-Buried Primary Cable--The Case for Planned Replacement," Transmission & Distribution, 1989, July, 68-71

"Due to increased URD cable-failure rates, electric utilities have been taking steps to develop cable-replacement programs. The author presents data on estimated URD cable failures from 1985 to 1994. It is found that if underground cable failure rates continue to rise, their planned replacement becomes increasingly important.

The importance of cable replacement programs has begun to show with increased failure rates. However, only six out of approximately 70 utilities surveyed had planned replacement programs.

Cable replacement programs with the greatest success have dedicated staffs that monitor cable failures."

Figure 1 displays a graph of estimated URD cable failures per thousand miles for the years 1985 to 1994. Data was presented for life spans of 24, 26, 28 and 30 years. Table 1 presents the estimated miles of failing cable, showing the miles for 24, 26, 28 and 30-year life cable for the years 1985 through 1994.

Search terms and ID: Cables, Data, Journal Article, 96

Meniconi, 1996

Meniconi, M.; Barry, D.M.

"Power Function Distribution: A Useful and Simple Distribution to Assess Electrical Component Reliability, The," Microelectronic Reliability, 0026-2714, 1996, 36, 9, 1207-1212, Elsevier Science Ltd., UK

Because of its relative simplicity, power functions (exponential distributions) are suggested over complex models like Weibull and lognormal for application in determining component reliability. It may also be more accurate in terms of predicting the stage of a component's life. Application has been tested on EMP data sets.

Several power function equations are presented. The power function is demonstrated for EMP tests on transistors. Curves for reliability and hazard versus time are presented as a case study for differing temperatures.

Search terms and ID: Non-specific, Equations, Technical, Report, 85

Miller, 1995

Miller, George

"Analyzing Transformer Insulating Fluid," EC&M, 1995, November

Insulating fluid is a major component of transformers. Because the oil breaks down in a predictable manner, regular checks can determine trends. Oil tests provide an indication of interior conditions and can prevent unscheduled outages. Several oil tests are listed and described.

Study by Hartford Steam boiler over 20 years indicates that 13% of transformer failures are due to inadequate maintenance. The average failure of these transformers is at 11 years, versus the expected time of 25 to 30 years.

Search terms and ID: Transformers, Monitoring, Journal Article, 22

Mintz, 1990(1)

Mintz, J.D.

"Developments in XLPE-Insulated Underground Distribution Cable," Electricity Today, 1990, April, 2, 3, 30-31

This report examines the status of XLPE-insulated power cables, and the designs of cable installations using XLPE-insulated cables. It uses the information on the life of older cable types and designs and judgment to estimate the expected performance of XLPE-cable and designs. The report was meant to help utility engineers understand developments in cable design, so that they can develop cable standards that would result in the installation of the most appropriate cable. The report describes the basis of the cable life estimates, describes the technical characteristics of XLPE-cable, and presents expected performance of older and XLPE-cable designs.

The report presents data on life in a manner that is unusual and difficult to interpret. Table 2 provides the Approximate Average Age of cable insulated with butyl rubber, high molecular weight PE, and crosslinked polyethylene. Table 3 presents expected effects on cable life of extra clean XLPE improved material handling, improved extruded thermoset shields, processing changes and jackets. In the text the average age seems to be defined as "when failure rates go above 3 faults per year per 100 km" (0.0483 per mile).

Search terms and ID: Cables, Data, Causes, Journal, 256

Mintz, 1990(2)

Mintz, J.D.

"Developments in XLPE-Insulated Underground Distribution Cable - Part II: Options to Current Cable Design," Electricity Today, 1990, May, 2, 4, 43-46

This report is Part II of an earlier report with the same title. It extends the results of that earlier report. It examines several optional materials and processing changes that at the date of publication (1990) were expected to lengthen the life of XLPE-insulated cable. The author discusses cable specifications, the applicability of traditional qualification tests to the new types of cables, and production testing. The author also provides estimates of the useful life of different new (as of 1990) cable designs.

Table 2 provides the author's estimates of the expected life of different cable designs. Six designs are considered. The designs differ in their use of the following items: full metal barrier, coated foils, swellable powders, encapsulating jacket, purer semi-con material, thure triple extrusion, extruded shields, strand filling, tree retardant material, PE jacket, PVC jacket, Extra clean XLPE, dual tandem extrusion, bonded shield, thicker insulation, super smooth shield, dry cure, salt cure, silane cross linking.

Search terms and ID: Cables, Data, Causes, Journal, 257

Mintz, 1987

Mintz, J.D.

"Survey of experience with polymeric insulated power cable in underground service, Phase III," CEA No. 1117 D 295, 1987, October, CEA, Montreal, Quebec, Canada

Previously, in Phases I and II of this project, data were collected on cable system faults up to 1983. In Phase III, the survey was modified and data were gathered for several more years, up to 1986. Thirty Canadian utilities supplied information on their underground power cable systems. Information available from the U.S. and Europe was used to augment this data. The cable failure rate (excluding dig-ins) over the last 4 years was between 0.9 and 1.3 faults per 100-conductor km per year. American and European rates were less than 0.5. The failure rate from dig-ins was about 0.3 to 0.7. Based on the current installed plant, cable systems with an average age of 10 years have a failure rate of 2 per 100 km per year. With an age of 15, they have a rate of 5 to 6. Accessory faults accounted for 55% of the failures on cable systems. A PC-based computer program was developed to administer the survey and a modified version is available for utilities to keep track of their own cable system reliability.

"Only the title page, abstract, and table of contents for this document are found in the component reliability library. The entire report is available in the EPRI library.

Published in 1986 the data are somewhat dated, but this is an in-depth study. Unfortunately the report does not derive failure or hazard rates with age and it is not straightforward to derive failure or hazard rates with age from the information presented. 28 Canadian utilities contributed data on failure rates. Data covers the period 1977 to 1986. First study (1984) was based on approximately 9500km of XLPE cable. Page 11 gives an average failure rate of 1.13 faults per 100km. with a range from 0.35 to 6.05 faults/ 100km/year with an average cable age of 7 years. Page 13 presents a graph of failure rate with age for cable aged approximately 4 to 19 years. Data are provided for three systems. Table IV, page 14 presents failure rates fro terminations, elbows, and splices from the 1984 Canadian study and an unidentified American study. The next section provides data from non-Canadian sources. Table VI has data from Memphis and Duke for HMPE 175, 240, and 260 mil, XLPE 175, 240, and 260 mil (rows). Data provided are km of cable, kV, kV/mm, 1985 failure rates, 1986 failure rates. Table VII provides Northwest Electric Light and Power Association (NELPA) data. Cable covered (rows) include HMPE 175, 220, 260, 295 mil unjacketed, XLPE 175, 220, 260 mil unjacketed and 175 mil jacketed, tree-retardant HMPE, and tree-retardant XLPE. Data provided are km of cable, kV, kV/mm, number of faults, and failure rate for 1985. Table VIII provides NELPA data for elbows, splices, and terminations. Data provided are kV, number in service, number of failures, and fault rate. Table

IX reports data from an AEIC/EEI survey. Data are for XLPE jacketed in duct <1.6kV/mm, XLPE jacketed in duct >1.6kV/mm, XLPE jacketed direct buried <1.6kV/mm, XLPE jacketed direct buried >1.6kV/mm, XLPE un-jacketed in duct <1.6kV/mm, XLPE un-jacketed in duct >1.6kV/mm, XLPE un-jacketed direct buried <1.6kV/mm, XLPE un-jacketed direct buried >1.6kV/mm, HMPE un-jacketed in duct <1.6kV/mm, HMPE un-jacketed in duct >1.6kV/mm, HMPE un-jacketed direct buried <1.6kV/mm, HMPE un-jacketed direct buried >1.6kV/mm. Table X provides failure rates for various European countries for XLPE, LDPE, and EPR. The countries are Germany, Denmark, France, Ireland, Italy, Netherlands, U.K., Sweden, and Switzerland. Table 12 provides failure rates from France for terminations, splices, and transition joints. Table XIII begins the presentation of the 1984-1986 Canadian data. Rows in this table are years. Columns provide data on km of conductor installed, average cable age, failure rates from dig-ins, other, and total. Table XIII begins the presentation of the data gathered 1978 through 1986. Table XIII lists for each year in that period the km of conductor installed, the average cable age, and the failure rate from dig-in, other and total. Figure 3 graphs this same information. Table XIV shows failure rates for the years 1983 through 1986 by voltage class. Classes are 5, 15 and 25 or 28kV cable. Information is amount in km, average age, and fault rate. Table XV provides failure data for 1983-1986 for PILC cable and Other (mostly Butyl) cable. Information is amount in km, average age, and fault rate. Table XVI provides data on splices, elbows, terminations, and cable-other-dig-in (rows). Data (columns) include number installed, fault rate, conductor length, and fault rate/ 100 km/yr."

Search terms and ID: Cables, Data, Report, 264

Mok, 1996

Mok, Y.L.; Chung, T.S.

“Application of Customer-Interruption Costs for Optimum Distribution Planning,” Energy, 1996, 21, 3, 157-164, Elsevier Science Ltd.

"This paper presents a sample application of the value-based distribution reliability planning and modeling methods found in the Billinton material. Eleven alternate capital-improvement projects to a distribution system are compared by total cost, in a total cost minimization. The distribution system reliability modeling formulas using series-parallel reduction with component failure rates and restoration times are the same as those in Billinton’s publications, with some simplifications. In addition, the authors use minimal cut-set theory for mesh-distribution systems. This method isn't discussed: the results are just shown. Tabulated values of failure and reliability data for distribution components are used in the reliability modeling. The authors state this type of component data from historical performance is usually available from a utility’s database. The average outage rate (f/yr), average annual outage time (hr/yr), average outage duration (hr) are the reliability indices by which alternate plans are compared. Customer interruption costs differentiated by sector, duration, and season are used to calculate the customer cost part of total cost.

Method to determine the reliability cost and worth of the distribution system is presented. The relationship between reliability cost, reliability worth and reliability at the specified load point are obtained, and the optimum system reliability with customer interruptions is determined from the minimum cost to the utility. Uses minimal cut set theory to determine annual customer interruption cost with respect to outages, load and cost of interruption."

Provides reliability data but with no references to source. Table 1 provides data for Busbars, circuit breakers, transformers, fuses, and lines (rows). Data provided include (columns): permanent failure rate (f/year), active failure rate (f/year), repair time (hr), maintenance outage rate (out/yr), Maintenance outage time (hr), switching time (hr), and sticking probability. 80% of unavailability is associated with 11 kV distribution systems. Consumer-interruption cost is difficult to calculate because it is dependent upon consumers' perception of worth of interruption.

Search terms and ID: Multiple, Data, Financial, Journal Article, 46

Moravek, 1994

Moravek, James

“Benefits of using a harmonic monitoring program,” Electrical Construction & Maintenance, 1994, September, Intertec

The proactive approach to harmonics is to monitor loads on equipment susceptible to harmonics. Monitoring consists of two parts; establish a baseline reading to determine if the tested equipment is operating within its stated parameters, if not, take corrective actions. If the equipment is operating within its parameters, we should evaluate the loading to determine what derating should be applied when adding future loads. The author recommends the following equipment to be monitored for harmonics: transformers, power distribution units, neutrals for feeders and branch circuits, UPS systems, emergency power generator used in conjunction with UPS systems or other significant nonlinear loads, capacitors, circuit breakers. The paper gives some derating guidelines.

Recommends a monitoring program to assist in identifying problems caused by harmonics.

Harmonics can cause:

-Overheating of electromagnetic equipment and neutral conductors

-Malfunctioning of control systems dependent on wave-form

Equipment to monitor for harmonics includes: transformers, power distribution units, neutrals for feeders and brand circuits, UPS systems, Emergency power generator sets, capacitors, circuit breakers.

Search terms and ID: Multiple, Monitoring, Causes, Journal Article, 57

Muir, 2000

Muir, Fiona

"1999/2000 Quality of Supply Report," NM396, 2000, 28-Jun, Scottish Power

Report summarizes the quality of supply to customers in the Wales, Merseyside and Cheshire areas. Descriptions of system failures due to mechanical and natural forces are described simply for system customers.

There are a lot of general information data tables, but not a lot of failure data. Table 2 (page 20) provided fault distribution data for low voltage and high voltage overhead, underground and other cables.

Search terms and ID: System, Data, Report, 125

Nelson, 1998

Nelson, R.F.

"Reliability-centered power line management - inspection process, measurement techniques and data management considerations," Colloquium on Distribution overhead lines - economics, practice, and technology of reliability assessment, 1998, 289, 3/1 - 3/24, IEE, London, UK

While methods and practices for maintaining the reliability of overhead line systems may differ between US and UK electric utilities, there are more similarities than differences. Impending deregulation has forced more immediate changes within the industry to evaluate current design and maintenance practices to achieve the most from available assets at the least cost. As utility line managers desire more quantitative inspection information by which to optimize required maintenance and forecast line performance and maintenance needs, line inspectors are required to utilize state-of-the-art tools and techniques capable of providing such information. The intent of this paper is to review tools and techniques, which can enhance the data, obtained during the inspection process for overhead wood pole lines. The ability to consistently collect and report quantitative data is a critical component of the Reliability-Centered Management (RCM) approach to overhead line management.

Provides several graphs indicating the accuracy of various tests in predicting MORGL, MORBP, and Tip Load. Since none of these terms are defined accurately in the text the usefulness of these relationships is hard to judge.

Search terms and ID: Poles, Monitoring, Proceedings, 242

Ngundam, 1983

Ngundam, J.M.; Short, M.J.

"Prediction of Circuit Breaker Reliability," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 137-144, IEE, London, United Kingdom

This paper contends that better reliability can be achieved by better design and production and by the use of better materials. Reliability is as dependent on the material dielectric and mechanical properties of components as on the operating conditions. The author models failures within a circuit to determine the probability of the circuit breaker being activated, and from this the probability of circuit breaker deterioration and failure. Deterioration reduced circuit breaker reliability at each stage. The article also suggests that components can remain economically feasible if regularly maintained. System reliability is dependent on assessing component deterioration.

In Table 4 fault data is provided for overhead lines, transformers, switchgear, and cables (rows) for varying fault types. Fault rates (columns) are provided for 400kV and 275kV. Charts of reliability versus time integrate data such as the number of faults, location of faults, and line length are presented. Data is from 1968 through 1974 from the CEGB.

Search terms and ID: Multiple, Data, Technical, Journal Article, 9

Patton, 1968

Patton, Alton D.

"Determination and Analysis of Data for Reliability Studies," IEEE Transactions on Power Apparatus and Systems, 1968, January, PAS-87, 1, 84-100, IEEE

Paper discusses estimating required component parameters from field data. Field data can be used to estimate component outage rates and mean outage durations. The estimated component parameters can then be used in reliability analyses. Confidence levels and conditions for pooling data between companies are also presented.

Several regression equations associated with the analysis are presented. Figure 2 displays lightning-caused transient-caused forced outages of unshielded, single-pole 69-kV transmission lines. Table I Displays regression analysis results for transmission line outage rates for transient-cause forced outages (lightning and nonlightning), persistent-cause forced outages and scheduled outages. Figure 3 displays distribution of time periods between transient-cause forced outages and scheduled outages. Figure 4 presents distributions of persistent-cause forced outage durations for 69-kV transmission lines. Figure 5 presents the distribution of scheduled outage durations for shielded H-frame 69-kV transmission lines. Table II lists transmission line outage duration statistics for persistent-cause forced and scheduled outages. Figure 6 presents the distribution of time periods between scheduled outages of a 138/12.5 kV, 20 MVA, FA substation transformer. Tables IV and V display substation component forced and scheduled outage rates for various voltage transformers, circuit breakers, buses and air switches. Figure 7 displays the distribution of persistent-cause forced outage durations for 69-kV distribution substation transformers. Figure 8 presents the distribution of 69-kV transmission manual switching times and transformer fuse replacement times. Table VII presents substation component persistent forced outage duration and switching time statistics for transformers, circuit breakers, buses, air switches, annual switches and fuses. Table VIII displays substation component scheduled outage duration statistics for transformers, circuit breakers buses and air switches. In the discussion portion of the paper, Figures 9 and 10 present outage per year versus line exposure distance prediction lines with confidence limits. Figure 11 displays data comparing outages per year per mile versus line exposure distance.

Search terms and ID: System, Data, Journal Article, 118

Paulson, 1966

Paulson, N. L.; Carey, W. L.

"Outage Analysis Spots Trouble Areas," Electrical World, 1966, 21-Mar, 88-89, 153, McGraw-Hill

Paper discusses how outage reporting has evolved into a company-wide procedure for Portland General Electric.

Only data from 1964 is presented: Underground direct-buried primary cable circuits have one-fifth the failure rate per circuit-mile of overhead primary circuits. Underground secondary system, including distribution transformers, has one-tenth the customer outage frequency rate of the overhead secondary system. Dig-ins, resulting in cable failures, are the major cause of outage to the underground system. Average customer outage duration is nearly three times as long for an underground system as for an overhead system.

Search terms and ID: System, Monitoring, Journal Article, 105

Payne, 1995

Payne, K.G.; Brown, L.S.

"Prioritizing Supply Infrastructure Works Using Statistically Based Analyses," The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 157-161, IEE, Norwich, UK

Statistical model to predict deterioration so that a defined failure can be predicted, consequences understood, and corresponding losses calculated. Illustrates reliability analyses using fault trees.

Paper is exclusively qualitative, providing models for yes/no decisions regarding prioritizing power equipment replacement investments. Case study of power distribution's role in the operation of the London Underground.

Search terms and ID: System, Financial, Technical, Proceedings, 73

Peelo, 1996

Peelo, D.F.; Meehan, J.; Bergman, W.J.

“On-line condition monitoring of substation power equipment utility needs,” CEA No. 485 T 1049, 1996, December, Canadian Electricity Association, Montreal, Quebec

The report examines the application of substation equipment on-line condition monitoring form a utility perspective. Equipment failure and outage statistics are examined. Equipment attributes that could be monitored and the derived value are listed. The basic conclusion of the report is that equipment on-line condition monitoring can provide needed and justifiable value if applied in the broad context of achieving predictive maintenance and improved equipment utilization, functionality and life management

We do not have the whole report. Only the executive summary, conclusions, recommendations, and references. We should attempt to obtain the whole report.

Search terms and ID: Multiple, Monitoring, Report, 51

Philipson, 1992

Philipson, Lorrin

“Maintaining reliability,” Electrical world, 1992, June 1, 15, McGraw-Hill

Discusses the approaches taken to distribution system maintenance at several utilities. Overall theme is strategies for dealing with reduced budgets and other constraints while maintaining reliability. Suggests that many utilities are so reluctant to make capital investments that they are not making distribution system investments with payback periods as low as 3 years.

Search terms and ID: Multiple, Maintenance, Monitoring, Journal Article, 217

Power System Engineering Committee, 1973

Power System Engineering Committee

"IEEE Standard Definitions in Power Operations Terminology including terms for reporting and analyzing outages of electrical transmission and distribution facilities and interruptions to customer service," Std 346-1973, 1973, 12-Nov, IEEE

Supplies definitions for terms associated with component outages and service interruptions.

Search terms and ID: Other, Other, Report, 268

Procaccia, 1997

Procaccia, H.; Cordier, R.; Muller, S.

"Application of Bayesian statistical decision theory for maintenance optimization problem," Reliability Engineering and System Safety, 0951-8320, 1997, 55, 143-149, Elsevier Science Ltd., Northern Ireland

A Bayesian approach, combined with operating feedback, risk consequences and economic consequences, can be used to determine optimized Reliability-Centered Maintenance (RCM) policies. This method is proposed for instances where 1) there is little operating feedback concerning rare events affecting a critical piece of equipment, and 2) when the goal is to optimize the maintenance frequency of critical equipment. Use of feedback from observations is limited because, as the paper contends, Bayesian modeling is suited for the evaluation of probabilities in an uncertain space. Paper discusses diesel engines at nuclear power plants.

Some observations are presented for which the model is compared to. The observations include yes or no answers to a question of the probability of a scratch occurring in block linings of a diesel engine over a certain operating time. The types of scratches considered are nicks, short scratches, long scratches, short deep scratches, long deep scratches, and scratches entailing oil leak or excess crankcase pressure. A model is used to present a graph establishing a law of failure versus the number of starts. A decision tree is also presented with anecdotal data.

Search terms and ID: Other, Technical, Monitoring, Journal Article, 82

Pryor, 1987

Pryor, B.M.

"Factors affecting the deterioration of HV switchgear," Revitalising transmission and distribution systems, 1987, February 25-27, 273, 92-97, IEE, London, United Kingdom

"A mainly qualitative description of the factors affecting the deterioration of HV switchgear. Suggests that for equipment over 25 years of age where other test methods are not available select units should be taken out of service, disassembled, and thoroughly inspected.

The paper discusses factors that affect the deterioration of HV switchgear. These factors are operational/design features, fault rating and switching conditions, thermal limitations, age, maintenance requirements, environmental aspects, dielectric considerations and spares availability."

Discusses voltage range from 3.3 to 420 kV plain-brake circuit-breakers. Typical problems found are:

- Obsolescence in design
- Fault levels beyond capability
- Use other disconnector
- Fitted with dependent manual operating mechanism
- Not properly grounded

Major thermal deterioration problems are associated with outdoor distribution and transmission equipment where oxidation of external joint faces can occur.

Search terms and ID: Switches, Monitoring, Causes, Proceedings, 53

Pugh, 1997

Pugh, J.S.; Castro Ferreira, L.R. ; Crossley, P.A.; Allan, R.N.; Goody, J.; Downes, J.

"Reliability of Protection and Control Systems for Transmission Feeders, The," Development in Power System Protection, 1997, March 25, 434, IEE

"This paper introduces a technique for assessing the reliability of protection and control systems using reliability models and event tree analysis. An event tree provides a visual way for calculating the probability of a sequence of events given single event probabilities. This technique allows a quantitative assessment of dependability (the probability that the protection operates satisfactorily when required) and security (the probability that the protection does not operate when not required) to be made. These assessments can then be used to determine the effect of integrating different protection and control functions into a single unit.

The paper presents dependability results for feeder protection schemes based on differential protection and distance protection and combined differential and distance protection. The paper also considers the effect on the dependability of these schemes of including a separate and an integral inter-trip. It is worth noting that the model is static, so that there is no change in event probabilities due to aging or wear.

Combining functions into a single unit can have a degrading effect on reliability due to the increased risk of common mode failures."

Page 12 provides what is characterized as illustrative data on failure rates for several components. The components include power supply unit, communications links, intertrips, digital outputs, and others. The author uses abbreviations for components and without more understanding of these systems component identification is uncertain.

Search terms and ID: System, Technical, Data, Journal Article, 38

Radtke, 1991

Radtke, Michael I.

"Failure Analysis Improves Distribution Transformer Quality," Transmission & Distribution, 1991, November, 82-86

Wisconsin Public Service Corp. (WPS) Green Bay, WI, serves more than 320000 electric customers in a 10000 sq mi area of Northeastern Wisconsin. During the 1970's WPS kept transformer failure and repair data and suspected marked differences between manufacturers. However, the company had no formal way of analyzing the data. During the mid 1980s, WPS developed a formal transformer failure analysis program. The program was initiated so that WPS could measure the reliability of individual manufacturers, develop accurate failure costs, and improve communications between transformer manufacturers and users. The author describes how WPS has found significant failure rate reductions during the 5 yr of formal failure analysis. For 10 and 15 kV single-phase overhead units, they have seen a 33% reduction in failure rate from an average of 1.09 for the 1983-through-1986 period to 0.73 for the 1987-90 period.

The paper presents hazard rate and failure rate data. Hazard rate is defined as the number of failures in a year divided by the number of units in service at the beginning of the year. Failure rate is defined as the total number of failures divided by the total unit years of service. Figures 4 and 5 display the failure rate for 10-15 kVA overhead transformers and 25-250 kVA overhead transformers, respectively, for varying manufacturers. Figure 6 displays the transformer failure rate for single-phase pad-mounted transformers for varying manufacturers. Figures 7 and 8 display transformer failure analysis for 10 kVA and 25 kVA, respectively, overhead transformers from 1987 to 1990 by comparing failure cost adder dollars versus manufacturers.

Search terms and ID: Transformers, Data, Journal Article, 95

Reder, 2000

Reder, W.; Flaten, D.

“Reliability centered maintenance for distribution underground systems,” 2000 Power Engineering Society Summer Meeting, 2000, 1, 551-556, IEEE, Piscataway, NJ

With the technical advent of predictive testing for electric distribution facilities, reliability centered maintenance (RCM) principles can now be applied to maintain underground systems. This paper reviews the history and concepts of RCM, discusses the typical RCM underground process, identifies technical steps for applying RCM to manage distribution underground cable, and discusses the benefits along with the key success factors for managing underground facilities in this fashion. Finally, a case study is discussed demonstrating the application and results of RCM for distribution underground systems.

Suggest that testing can significantly increase the effectiveness of cable replacement programs. Used Ultra Power Technologies Inc. cable testing, but provides no further information on the test performed.

Search terms and ID: System, Financial, Maintenance, Proceedings, 237

Reinhart, 1997

Reinhart, Eugene R.

“Keeping power plants profitable,” Mechanical engineering-CIME, 1997, April, 119, 4, 74

Discusses advances in nondestructive evaluation of generator components such as turbine blades, turbine rotors, and pipes. Considers how these tests can improve maintenance procedures.

Search terms and ID: Generators, Monitoring, Maintenance, Journal Article, 207

Renforth, 1998

Renforth, L.

“Economic case for reliability centred maintenance in the UK - a pilot study,” Colloquium on Distribution overhead lines - economics, practice, and technology of reliability assessment, 1998, 289, 5/1 - 5/5, IEE, London, UK

The purpose of the pilot project was to demonstrate the application of inspection techniques and assessment methodologies aimed at improving the quality of field data to enable sound maintenance decisions to be made regarding wood pole OH lines. Reliability-Centred Power Line Management, which encompasses practical use of inspection technologies and assessment methods, has proven to result in very favourable cost-benefit ratios in the US. The pilot project applied an inspection and assessment approach such that the REC could identify the applicability of RCM to the management of their overhead lines. Whilst various levels of assessment methodology are possible any solution must consider the cost benefit of extending service life using RCM in both the short and the long term. In order to compare the maintenance options a life-cycle cost analysis has been carried out to compare the options (rebuild, selective repair, selective replacement etc) over a 20-year cycle by applying the concept of Net Present Value.

Some data is provided on the cost of inspections, pole repairs, and pole replacement in the UK.

Search terms and ID: Poles, Monitoring, Proceedings, 244

Rhoten, 1971

Rhoten, G. P.

"Evaluation of Service Reliability," 1971, 1-6, IEEE

Paper discusses a system implemented in Texas in the late 1950s that processes service interruptions as the basis for reliability evaluation.

Some data is presented, but only to highlight a point. Source of data is unknown.

Search terms and ID: System, Data, Journal Article, 102

Rhoten, 1961

Rhoten, G. P.

"General Program for Processing Distribution Data, A (Orients Distribution Computer Data)," Electrical World, 1961, Dec. 18, 45-48, 126, McGraw-Hill

Paper discusses the location, accumulation, processing and monitoring of interruption data from a 1,000,000-foot square area grid. A computer is used to process information regarding distribution property, equipment or customer located on the grid.

Paper presents no aging asset data and does not lend itself to this study.

Search terms and ID: System, Monitoring, Journal Article, 104

Roberts, Jr., 1993

Roberts, Jr., W.T.; Mann, Jr., L.

"Failure Predictions in Repairable Multi-Component Systems," International journal of production economics, 1993, 29, 103-110, Elsevier

Authors discuss that multi-component repairable systems cannot be modeled by continuous distributions, such as the Weibull. Nonhomogenous Poisson Process (NHPP) models are recognized as better representing repairable systems. Since most systems are repaired, not replaced, NHPP are better. The objective is to prove that a simulation based on Weibull parameters of major components is able to duplicate the NHPP model. The simulations can provide failure prediction results that can be traced to individual components. The simulation can identify a finite number of parts that contribute to the overall system downtime and this information can guide maintenance.

System components for which failure data is provided are not identified. Data charts are presented that display reliability versus time for both NHPP and Weibull.

Search terms and ID: System, Technical, Journal Article, 27

Robertson, 1998

Robertson, C.

"Inspection & data collection procedures - present & future," Colloquium on Distribution overhead lines - economics, practice, and technology of reliability assessment, 1998, 289, 4/1 - 4/14, IEE, London, UK

Discusses inspection and maintenance responsibilities under UK regulations. Describes a typical current inspection program for a hypothetical set of poles. Provides a typical inspection questionnaire.

Search terms and ID: Poles, Monitoring, Proceedings, 243

Saddock, 1976

Saddock, H. G.; Bhavaraju, M. P.; Billinton, R.; DeSieno, C. F.; Endrenyi, J.; Jorgensen, G. E.

"Common Mode Forced Outages of Overhead Transmission Lines," IEEE Transactions on Power Apparatus and Systems, 1976, May/June, PAS-95, 3, 859-863, IEEE

As more transmission lines are constructed in already occupied right-of-way, this paper posits that there is a need for definition and data collection of common mode outages of multiple transmission lines. This paper outlines a method for reporting of common mode outages of multiple transmission lines, and presents indices of common mode outages and methods for calculating said indices.

No real data is presented. Paper presents suggested report forms for recording common mode outages of multiple transmission lines. Sample data and calculations are presented.

Search terms and ID: Cables, Data, Journal Article, 115

Sakai, 1983

Sakai, Takami; Kumamaru, Toshio ; Sugawara, M. ; Sasagawa, H.

"Development of the Computing Program for the Reliability Evaluation of Equipment," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 127-131, IEE, London, United Kingdom

This article discusses a computing program (TOSPEC) for analyzing the probability of failure of a system. It has such features as not requiring fault trees or event trees according to schematic diagrams; it can evaluate the effect of failure of each component; it can calculate reliability and availability; and it can calculate minimal cut set.

The article contains analytical diagrams for the probability of failure and a diagram displaying the sensitivity of failure probability to the interval of automatic testing.

Search terms and ID: System, Technical, Proceedings, 7

Salis, 1999

Salis, G.J.; Safigianni, A.S.

"Long-Term Optimization of Radial Primary Distribution Networks by Conductor Replacements," Electrical Power and Energy Systems 21 (1998), 1999, 21, 349-355, Elsevier Science Ltd.

The optimum planning of power distribution networks is important because these networks are close to customers and are characterized by high investment and operational cost. This paper develops a method for technoeconomical long-term optimization of currently operating radial primary power distribution networks. The method utilizes results and suitably modifies computational procedures described earlier in the literature. The method identifies the optimal (least cost) timing and location of conductor replacements at the network segments so that the network may approximate its long-term optimum form. The method takes into account the realistic locations and growth of the load served by the examined network and specific technoeconomical constraints.

For each conductor in a network segment, the total cost of losses is calculated as the net present worth of annual losses (over the planning horizon) per unit length of the segment, assuming constant losses beyond a pre-specified period within the plan horizon. Defining cost as total loss plus operational costs per unit length for the component of interest, the decision function is defined as the difference between two cost functions that correspond to the component and its upgrade.

A so-called “long term” algorithm based on the above defined decision function is proposed that accounts for technical constraints related to power flow in the network segments, thermal short-circuit strength of the conductors, and conductor tapering in the network segments. The algorithm also examines the network voltage profile. Since the replacement proposals are sequential, upon termination of the long term optimization routine, the algorithm runs scenarios that examine the improvement of the economical results for the proposed replacements being executed earlier than the years calculated by the long term (sequential) optimization routine.

The technique is applied to a feeder of the primary power distribution network of the area of Xanthi, Greece. This appears to be a straightforward decision problem and the modeling is elementary. There is nothing interesting here about aging assets, and the main issue is mitigating losses.

Final economic results found that profits from the savings in reduced losses more than compensated for the system's required investment."

Optimum selection is closest to the optimum that satisfies specific technical constraints with the minimal possible cost.

Search terms and ID: System, Financial, Technical, Journal Article, 33

Sanwarwalla, 1995

Sanwarwalla, Mansoor; Weinacht, Rick

Aging Management Through Condition Monitoring of ASCo Solenoid Valves and NAMCO Switches,” Plant Systems/Components Aging Management, 1995, 316, 51-57, ASME

This paper advocates that periodic replacement costs of ASCo solenoid valves and NAMCO limit switches can be decreased by controlling aging through baseline characteristic/performance criteria and periodic condition monitoring. These processes allow for the optimization of the qualified life of the components, reducing the replacement frequency, and thus equipment replacement and maintenance costs. The components are used in nuclear power plants.

Material properties of the equipment and a summary test plan are presented. No aging data is presented.

Search terms and ID: Other, Causes, Journal Article, 81

Schimmoller, 1998

Schimmoller, Brian K.

“Shake those Boeing blues,” Power engineering, 1998, September, 102, 9, 12

Briefly describes the reliability centered maintenance (RCM) program at TVA's Cumberland Fossil Plant

Search terms and ID: Generators, Maintenance, Journal Article, 208

Serwinowski, 1997

Serwinowski, Mark A.; Hatch, David C.

“Prudent Management of Utility Assets—Problem or Promise?,” 1997, 475-478

Paper discusses strategies to improve asset management by way of Economic Value Added (EVA). EVA focuses on increasing positive cash flows and minimizing negative cash flows. Tools that can be used to increase EVA include value-added engineering, remedial strategies, market valuation strategies, best use analyses, etc. EVA helps reach decisions regarding improving, selling, or deferring assets. Improving EVA as part of total asset management helps maximize capital resources, reduce operating expenses, increase financial returns and improve intangibles like corporate image.

Aging assets not explicitly discussed. General framework for use of EVA presented.

Search terms and ID: Non-specific, Financial, Report, 37

Settembrini, 1991

Settembrini, R.C.; Fisher, J.R. ; Hudak, N.E.

“Reliability and Quality Comparisons of Electric Power Distribution Systems,” Proceedings of the Transmission and Distribution Conference, Dallas, 1991, September, 704-712, IEEE

Seven common distribution systems (simple radial, primary auto loop, underground residential distribution, primary selective, secondary selective, distributed grid network, spot network) were analyzed by comparing field performance and theoretical calculations for frequency and average duration of outages. Distribution systems were then ranked by reliability and ability to deliver "clean power.” The selection criteria enable distribution engineers to choose a system of reliable power based upon customer needs. Reliability is compared by the number of outages per year;

average duration of the outage; number of momentary interruptions per year; power quality; voltage regulation; and voltage disturbances.

Failures per year and average downtime per failure for primary feeders, transformers, and secondary line are presented. No source is cited. The seven distribution systems analyzed are 1) Simple Radial; 2) Primary Auto Loop; 3) Underground Residential; 4) Primary Selective; 5) Secondary Selective; 6) Distributed Grid Network; and 7) Spot Network. Grid Networks were found to be the most reliable.

Search terms and ID: System, Technical, Data, Journal Article, 50

Settje, 1996

Settje, Scott

"Transformer Reliability: Some Considerations as Presented by Loss History," PWR Volume 30 Joint Power Generation Conference, Vol 2, 1996, 30, 257-263, ASME

"This paper argues that even though the reliability of transformers in North America, measured by Mean Time Between Failures (MTBF), is extremely good, it is important to examine the impact that a loss can have on the individual producer or user to gain insight into the economics of transformer failure. The paper argues that the multiple competitive alternatives in front of consumers could drive the cost cutting of the suppliers to a point where reliability and maintenance suffer. In the future, the paper continues, the power generation, transmission and other players will not carry the cost of spare transformers, and will depend more upon long life and reliability of single unit systems. If a supplier does not meet contractual agreements, the customer will have the option of seeking new suppliers and that will be a double blow to the less reliable supplier. This makes the issue of reliability versus cost cutting a very delicate matter. The paper then provides life expectancy curve of a transformer (life expectancy in hours versus the average temperature within which it operates) and the deteriorating effect of usage (curves that describe projected loss of life as a result of operating the transformer at temperatures above its nominal value for different number of hours). Looking at loss history, the paper concludes that loss frequency is highest for transformers in the 16-25 years old brackets and when the cost per occurrence is broken down, it is found that the resulting graph follows a typical bathtub curve. Utility transformer losses do not display the same costs per occurrence as industrial units due to the way the underlying insurance is purchased.

The paper further argues that in the future the utilities may need to purchase business interruption insurance to help supplement a less reliable generating or distribution system. The paper finally concludes that the preplanning and the application of a sound inspection and testing program will help reduce the frequency and mitigate the severity of failures since the result of a loss and the recovery is usually much higher than expected.

Article discusses common methods that utility and industrial users and owners can employ in a reliability program. Several graphs are presented that express life expectancy as a function of temperature, maximum loss of life curves that include penalties for operating under high temperatures, data tables for transformer losses, and a table for utility transformer losses by size."

Figure 1 provides life expectancy curve of a transformer (life expectancy in hours versus the average temperature within which it operates) and the deteriorating effect of usage (curves that describe projected loss of life as a result of operating the transformer at temperatures above its nominal value for different number of hours).

Table 1 provides numbers of losses for transformer with different years in service. Unfortunately sample sizes are not provided. Data is for the years 1985-1995. The data source is assumed to Arkwright Mutual Insurance, the affiliation of the author. Though this is not stated in the text.

Author states that transformers in North America are extremely reliable, but even small interruptions cause large problems and cost as much as $1 million per day. Costs dictate having reliability with out redundancy. Losses have differing costs for industrial units due to insurance purchasing programs. Loss of life is cumulative. Most transformer losses occur when transformers are 16 to 25 years old, but the highest rate of loss occurs when transformers have 1 to 5 and 36 to 40 years of service."

Search terms and ID: Transformers, Financial, Maintenance, Proceedings, 19

Sim, 1988

Sim, S.H.; Endrenyi, J.

"Optimal Preventive Maintenance with Repair," IEEE Transactions on Reliability, 1988, 92-96, IEEE

The paper develops a minimal preventive-maintenance model for repairable continuously operating devices whose conditions deteriorate with the time in service. The main ingredients of the model are as follows. The device is susceptible to two types of failure, namely, deterioration and Poisson. The device has a deterioration failure immediately following the completion of k stages of deterioration. The device is periodically removed from operation for minimal preventive-maintenance and this moves the device one stage back in its deterioration process. The device has also a Poisson failure, which occurs at the same constant rate in any of the deterioration stages, and this implies exponentially distributed times to failure for the Poisson failures. Moreover, the duration of each stage in the deterioration process is distributed according to a common exponential distribution. In addition to the deterioration process, the device goes through a minimal preventive-maintenance process for which the times to preventive-maintenance are distributed according to an Erlang distribution.

Defining the state as the stage in the deterioration process and the stage in the maintenance process, the paper presents steady-state equations for state transition probabilities as a set of algebraic equations. For the special case where there is only one stage in the preventive maintenance process, the paper presents an algorithm for sequential calculation of probabilities. For the general case, the paper calculates the mean time to preventive maintenance that minimizes the unavailability of the device defined as the sum of probabilities of unavailability due to Poisson and deterioration failures and unavailability due to preventive maintenance.

A model is presented that aims to minimize unavailability due to preventative maintenance, Poisson-distributed failures and deterioration failures. A Markov model is broken into stages where times to preventative maintenance use an Erlang distribution. Because Poisson failures cannot be prevented by preventative maintenance (PM), as the proportion of Poisson failures increases, the need for minimal PM decreases. The optimal time to minimal maintenance decreases as the mean repair time for deteriorating failures increases. As the Erlang parameter increases, the minimum availability decreases."

Search terms and ID: Non-specific, Financial, Technical, Journal Article, 36

Srinivasan, 1984

Srinivasan, N.; Prakasa, K.S. ; Indulkar, C.S.

"Novel Method for Filtering and Ranking of Critical Contingencies, A," Electrical Machines and Power Systems 1984, 1984, 9, 359-374, Hemisphere Publishing Corporation

New method that uses a line outage simulation technique to compute the new state of the system using a constant sensitivity matrix. Infinite norm is used to filter and rank critical contingencies. This new method uses no more computing power that previous methods. Additionally, this method provides a complete picture of the system with regards to line overloads, voltage levels and reactive power generations, as well as the value performance index under a contingency.

Provides a system scenario including bus voltages, angles, line flows and reactive power generations, along with the values of the performance indices following an outage.

Search terms and ID: System, Technical, Journal Article, 35

Stahlkopf, 1995

Stahlkopf, Karl

"Advanced maintenance technology improves power delivery systems," Electric light & power, 1995, June, 73, 6, 32

Discusses the growing application of reliability-centered maintenance (RCM), in particular EPRI's efforts in this area. The paper goes into some detail on new devices that support maintenance programs.

Search terms and ID: System, Maintenance, Journal Article, 210

Steed, 1995

Steed, John C.

“RTDE '95 - The Importance of Equipment Reliability,” Power engineering journal, 1995, June, 142-144

Summary of RTDE '95 conference, where consideration for equipment performance emerged as an aim. Topics discussed include methods of diagnosing reliability and plant failure statistics; design for reliability; condition monitoring; methods for improving distribution system reliability; and asset management. Some theories regarding predictive tools are now being questioned.

Cellulosic degradation byproducts provide a clue for fault and/or aging conditions. Furfuraldhyde is a product of paper aging found in insulating oil in certain high-temperature situations.

Search terms and ID: Non-specific, Other, Journal Article, 42

Steed, 1994

Steed, J.C.

“Experiences With Power Transformers in Southern Electric,” IEE Colloquium (Digest), 1994, 075, 3/1-3/6, IEE, London, United Kingdom

"The normally quiescent state of electrical transmission and distribution system plant does not draw attention to incipient faults, which may develop from the gradual deterioration of the equipment. These faults may be detected during routine maintenance but the ability to have detailed information on the state-of-health of transmission and distribution system equipment prior to carrying out maintenance work or alterations becomes a significant asset and adds an element of preventive maintenance to the operation of such assets.

The initial stage of condition monitoring consists of establishing the baseline parameters and recording the actual base line values. The next stage is to determine trends by observing the running condition and assessing the parameters previously determined for the baseline. The state of the present plant conditions can be obtained from the absolute figures and the rate of degradation can be estimated from the trend.

The benefits of condition monitoring can be summarized as reduced maintenance costs, quality control features provided by the results, limiting the probability of destructive failures, limiting the severity of any damage incurred and information provided on the transformer operating life. This information may enable business decisions to be made either on plant refurbishment or on asset replacement.

As transformers are generally extremely reliable, condition monitoring is usually performed on associated equipment such as on-load tap-changers. The paper mentions some of the techniques available to the user for monitoring the condition of power transformers. The topics (briefly) reviewed in this connection include oil analysis survey, winding movement detection, asset replacement survey, condition monitoring and asset replacement, and condition monitoring research. The paper concludes that condition monitoring must not be a purely scientific activity driven by technology but a maintenance approach driven by financial, operational, and safety requirements. It must provide information on plant condition to allow maintenance resources to be optimized and assist with the optimum economic replacement of the asset. No methodology is developed in this paper.

Case history of preventative maintenance based on establishing baseline parameters, recording the actual baseline, determining trends, and then determining the rate of degradation. Condition monitoring research can use fault statistics to monitor equipment failure rates and predict equipment lifetimes. It is also useful to conduct post-mortems to determine mechanisms of failure and to show multiple modes of failure. Types of condition monitoring discussed are oil analysis surveys, winding movement detection, and condition assessments. The author also states that there is a distinct difference between nameplate age and the insulation age in assessing transformer life."

Paper discusses preventative maintenance in predicting failures, but the paper does not discuss the failures themselves. Presents a condition assessment for power transformers that includes assessments of insulation systems, corrosion, general condition, and operation (reliability, availability of spares). Notes that for Southern the failure rate for h.v./l.v. ground mounted transformers is below 0.2% on a population of around 25,000.

Search terms and ID: Transformers, Monitoring, Data, Proceedings, 18

Steed, 1986

Steed, J.C.

"Using Fault Statistics to Monitor Equipment Failure Rates and Lifetimes," Revitalising Transmission and Distribution Systems, 1986, February 25-27, 273, 15-20, IEE, London, United Kingdom

The paper presents a national (UK) analysis of faults and illustrates some equipment aging failure rates and attempts to provide further information on plant lifetimes. For different components, the paper calculates hazard rate curves (the so-called bathtub curve, which plots hazard rate or the rate of occurrence of failures versus the age of the component). In doing so, some assumptions are made, among others, that system is non-repairable (each failure is replaced). The paper then studies the applicability of these assumptions to overhead lines, underground cables, pole-mounted transformers, ground mounted transformers, and HV switchgear, and calculates hazard rate curves when appropriate.

Article presents 20 years of data with 57 different direct cause categories. Faults are analyzed to illustrate equipment failure rates due to aging and plant lifetimes. Data is presented displaying aging failures and other failures versus time for systems of varying voltages. The article differentiates between failure rates and hazard rates. Hazard rates account for surviving equipment as well as failed equipment. Hazard rates are highest for equipment at the earliest and latest ages, creating a ""bath tub"" curve for Hazard rates versus age. Specific data is presented for varying cables, pole-mounted transformers, ground-mounted transformers, and switchgear. Aging should also be considered in conjunction of unacceptable failure rates, obsolescence, safety, etc.

Figure 1 plots number or fault reports (3 year moving average) for the low voltage (below 1kV system) versus year for deterioration due to aging and other direct causes.

Figure 2 plots number or fault reports (3 year moving average) for the low voltage (below 1kV system) versus year for overhead lines, underground cables, switchgear and fuses.

Figure 3 plots number or fault reports (3 year moving average) for the greater than 1kV and not exceeding 20kV, the 33kV and 66kV, and combined versus year for overhead lines and underground cables.

Figure 5 plots fault rate (3year moving average) per 100km versus year for 11kV cable.

Figure 6 plots %equal to or less than age shown versus age for pole-mounted transformers for 1985-1986.

Figure 7plots the hazard rate versus age of pole mounted transformers for 1985 -1986.

Figure 8 plots the hazard rate versus age in 3 year bands of pole mounted transformers and ground mounted transformers for 1985 -1986.

Figure 9 plots % of equipment within age range versus age in three-year bands for 11kV switchgear. Separate curves are provided for circuit breakers, circuit breakers excluding cable boxes and busbar joints, switchgear, switchgear excluding cable boxes and busbar joints.

For low voltage systems, there was a three-fold increase in aging failures between 1970 and 1985, and 25% of failures were due to aging. There was a 75% increase in aging failures for high voltage systems (and systems between 33kV and 66kV), with 18% of total due to aging. In general, 40 years is considered a reasonable lifetime for equipment.

Discussion in the paper suggests that age data is not included in the National Fault Investigation Reporting System (NAFIRS) in the United Kingdom"

Search terms and ID: Multiple, Data, Proceedings, 20

Stewart, 1998

Stewart, A. H.

“Enhanced management programs for overhead lines,” Colloquium on Distribution overhead lines - economics, practice, and technology of reliability assessment, 1998, 289, 6/1 - 6/19, IEE, London, UK

An overview of activities involved in developing a cost-effective line management program, improving maintenance forecasting, and opportunities for further advancing the state-of-the-art of management programs are presented herein. The paper presents information that is general in nature as well as more specific information regarding one leading U.S. utility’s experience in developing and refining its management program for overhead transmission lines. The unnamed U.S. utility uses a tool designated TL-MAP (Transmission Line-Maintenance Analysis Program) to enable analysis of the net present worth of various scenarios for performing transmission line maintenance. The tool makes use of a Markov model of changes in pole conditions. This is implemented via a decision tree structure. The use and capabilities of the tool are described in some detail.

Search terms and ID: Poles, Monitoring, Proceedings, 245

Stillman, 2000

Stillman, R. H.

“Modeling Failure Data of Overhead Distribution Systems,” IEEE Transactions on Power Delivery, 2000, October, 15, 4, 1238-1242, IEEE

Case studies of widespread rural and large urban overhead distribution systems are modeled as repairable systems. Homogeneous Poisson process (HPP) is used to describe exponentially distributed random variables, while nonhomogeneous Poisson process (NHPP) is used for randomly failure events that are neither independently nor identically distributed. In this study, the measure of the failure event is expressed in terms of rate of failure per 100 km days of line exposure, or ROCOF. The article demonstrates that a Laplace test statistic can determine how satisfactory that performance is in respect of a system of distribution lines. For systems subject to preventative maintenance, previous repairs and replacement randomize the time between failures, and thus ROCOF cannot be constant. It is shown through case studies not to be the case

that for lines subject to preventative maintenance, reliability is maximized and cost is minimized and ROCOF remains constant.

Data are presented from two case studies (an urban overhead distribution system and a rural overhead distribution system). Figure 1 displays a qualitative histogram of contribution of components to overhead line failures. It shows that poles, crossarms and insulators contribute to overhead failures at the earliest time interval, while conductor failures affect the system at later intervals. Figure 2 displays the cumulative failures of mercury lamps over cumulative operating time for linear (Group A) and non-linear (Group B) data. Table 1 displays the Laplace data for Group A and B in Figure 2. Figure 3 displays a trend chart of cumulative ROCOF per 100 km days versus cumulative operating time for a large urban system. The data is broken down in terms of pole failures, conductor failures, and total failures. Figure 4 displays a trend chart for sparse rural data, plotting cumulative ROCOF per 100 km days versus cumulative operating time. Figures 5 and 6 display pooled ROCOF data (and 90% confidence levels) for a large urban system and rural system, respectfully. ROCOF per 100 km of line is plotted against exposed line, in km.

Search terms and ID: Other, Technical, Journal Article, 91

Stillman, 1995

Stillman, R.H.; Mackisack, M.S.; Sharp, B. ; Lee, C.

“Case Studies in Survival Analysis of Overhead Line Components,” The Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995, March 29, 406, 210-214, IEE, Norwich, UK

Paper presents the hypothesis that the factor of greatest influence in the degradation of a component is aging. A three-parameter Weibull distribution is best distribution for the provided data. Three case studies of survival analysis are presented.

"Table 1 provides mortality data as a function of age, poles remaining, poles condemned, cumulative total, and characteristic population. Initial pole installation in 1964. For the Weibull model of failure, Table II presents the cumulative distribution, the probability density function, survival distribution, and the hazard rate. Figure 3 presents observed data and model-generated data of time-to-failure versus probability of failure. Figure 4 presents a model-generated sensitivity analysis of mean cost versus age to failure.

The data is probably from the Electricity Commission of Queensland, Australia."

Search terms and ID: Multiple, Technical, Data, Proceedings, 79

Stillman, 1994

Stillman, R. H.

"Probabilistic Derivation of Overstress for Overhead Distribution In-Line Structures," IEEE Transactions on Reliability, 1994, September, 43, 3, 366-374, IEEE

This paper shows how probability techniques can be applied to low and medium voltage distribution and high voltage sub-transmission lines, which use self-supporting single-pole structures. The probabilistic concept uses overlapping distributions in which the randomized stress induced by wind pressure is matched to the resisting strength of a pole structure. In this way a risk load is evaluated which optimizes structural strength and enhances the economic utility of the asset. Specific to the work is the inclusion of the degeneration of pole strength with age. This is important in distribution systems where wood is the most common construction material. The modeling uses Monte Carlo simulation to establish a failure risk of a line structure within a design return period and a life. Input to the model involves the static load imposed by line conductors and their ancillaries, random gust wind pressures (modeled by a Gumbel distribution), and a 3-parameter Weibull distribution to describe the dispersion of strength and degradation of the material. The pole overturning (wind) moment is compared to the degrading resisting (strength) bending-moment over daily or monthly intervals related to a designated lifetime. The work, for a large electric utility, analyzes treated hardwood and steel-reinforced concrete poles for new works, with emphasis on urban and semi-urban area construction. In the context of an urban and semi-rural environment, cost reductions in the order of 10% to 15% can be achieved.

Many of the figures are difficult to read due to poor copy quality. Figure 3 displays time-to-failure distributions (probability of failure versus years to failure) for differing pole types in various regions of Australia. Table 3 displays survival characteristics of SEQEB CCA poles. Data include pole age, years after installation, poles that failed/remained, number of poles at risk, and prediction, failure and reliability probabilities. Table 4 provides estimated Weibull parameters for Tasmainian CCA wood poles, S.E. Queensland CCA wood poles and S.E. Queensland concrete poles. Table 5 displays height factors in open country for the pole lengths in Table 1. These data include length, planting in ground, height above ground, maximum condition height, and GH(?), all in meters. Figure 4 is a histogram of monthly peak wind velocity for S.E. Queensland and Northern New South Wales, 1951-1991. Figure 5 displays a maximum monthly wind velocity analysis (Gumbel diagram) for S.E. Queensland and Northern New South Wales, 1951-1991. Table 7 displays an example of simulation output for the structure analyzed in Table 2. Figures 7a, 7b, and 7c display probability diagrams for CCA wood poles with applied wind moment versus resisting moment for years 1, 40 and 52, respectfully.

Search terms and ID: Poles, Data, Design, Journal Article, 99

Stoll, 1989

Stoll, Harry G.

"Least-Cost Electric Utility Planning," 1989, John Wiley & Sons, Inc., New York, New York

A handbook of electric utility planning. Focuses on the generation and transmission system, but has a good review of basic reliability approaches and models.

Search terms and ID: Non-specific, Financial, Technical, Book, 61

Tabors, 1993

Tabors, Richard

"Transmission System Management and Pricing: New Paradigms and International Comparisons," IEEE Transactions on Power Systems, 0885-8950, 1993, February, 9, 1, 206-213, IEEE

Paper discusses, in qualitative terms, three new paradigms. First, due to the economics of power generation and distribution, transmission, as opposed to generation, should be viewed as the market niche in the future. Second, the paper reviews transmission-pricing options, paying particular attention to short run marginal costing (SRMC) and long run marginal costing (LRMC). Third, the paper discusses international experiences in innovation in transmission system management and pricing.

Paper is grounded in policy discussions. The primary conclusions of the paper are 1) "While the new paradigm of a network utility is the likely outcome for U.S. and elsewhere, institutional constraints will make its accomplishment in the U.S. problematic and spotty," and 2) "Within the U.S., the transmission economics and pricing problem has been defined as one of 'open access,' and of Wheeling." The only data presented is the demand and generation, in megawatts, of electricity in various districts in the U.K.

Search terms and ID: System, Other, Journal Article, 89

Theil, 1987

Theil, G.

"Estimation of Reliability Indices for the Austrian High Voltage Network," Proceedings of the Ninth Power Systems Computation Conference, 1987, August 30, Butterworths

The paper presents a method for evaluating reliability indices of transmission networks. Many failures in electrical power distribution networks are dependent. Therefore, the reliability must be estimated for both the components and the system as a whole. The approach is based on a Bayesian procedure where the posterior distributions of expected outage duration and expected cycle time are calculated using (supposedly) known priors and data that are empirical averages of outage duration and cycle time. Assuming uniform priors and Gamma conditional distributions (distribution of empirically calculated averages for outage duration and cycle time given their expected values), the paper derives the posterior distribution of duration and cycle time and gives formulas for calculating different moments of these distributions. The approach is applied to reliability analysis of single lines, double circuit lines, transformers and for several types of failures such as independent outages, simultaneous outages due to short circuit or earth failures and missing operation of the protection system. These categories are identified as independent groups of failure events, which significantly contribute to the system unavailability.

Data from case studies are presented that found that dependent failures cannot be neglected because of unavailability of some categories containing dependent failure events have the same order of magnitude as the unavailability as the unavailability of independent single lines."

Data for single lines; double lines, parallel lines, transformers and busbars are presented. Single lines have the highest outage probabilities. Transformers have low outage probabilities but have longer outage durations. There are a high number of false breaker operations due to human error. Data is from the Austrian 110 kV and 220 kV network for the years from 1965 to 1984. The number of components in this system is not provided. Table 1 provides reliability indices for a number of components and component groups. The component and component groups (table rows) are: single line, double circuit line, parallel line, transformers 220/110 kV, simultaneous outage due to short circuit or earth failures, double outages, triple outages, false breaker operation, missing operation of the protection system (SVERS), busbar outages (SAFEL), busbar outages caused by human errors (SAFSA), outages of the type SVERS, SAFEL, SAFSA. The reliability indices (columns of the table) are: number of failure events, expectation of the outage duration, expectation of the cycle time, expectation of the outage frequency, expectation of the outage probability.

Search terms and ID: Multiple, Data, Equations, Proceedings, 26

Tolbert, 1995

Tolbert, L.M.; Cleveland, J.T.; Degenhardt, L.J.

“Reliability of lightning resistant overhead power distribution lines,” 1995 IEEE Industrial and commercial power systems technical conference, 1995, 147 - 152, IEEE

An assessment of the 32 year historical reliability of the 13.8 kV electrical distribution system at the Oak Ridge National Laboratory (ORNL) in Tennessee, USA, has yielded several conclusions useful in the planning of industrial power systems. The system configuration at ORNL has essentially remained unchanged in the last 32 years which allows a meaningful comparison of reliability trends for the plant's eight overhead distribution lines, two of which were built in the 1960s with lightning resistant construction techniques. Meticulous records indicating the cause, duration, and location of 135 electric outages in the plant's distribution system have allowed a reliability assessment to be performed. The assessment clearly shows how differences in voltage construction class, length, age, and maximum elevation above a reference elevation influence the reliability of overhead power distribution lines. Comparisons are also made between the ORNL historical data and predicted failure rates from ANSI and IEEE industry surveys.

The data is specific to a small sample of lines at Oak Ridge National Laboratory (ORNL), but interesting none the less. The report also provides a good bit of background on approaches to reducing lightning caused outages. A single 161 kV to 13.8kV primary substation supplies electrical power at ORNL in Tennessee. Eight radial 13.8kV overhead lines originate from the substation. The lines are 0.3 to 6.3 miles long and 23 to 42 years old. These lines are the subjects of the study. The text provides a fairly detailed description of the construction of the lines especially with respect to insulation and other types of lightning protection.

Table I provides the basic failure data. For each feeder the following is presented: construction voltage, elevation, length, age, frequency of outages, and cause. Causes are categorized as weather, animal, equipment, human error, or unknown.

Table II reclassifies the outages according to ANSI/IEEE Standard 493-1990 and compares ORNL experience to industry experience as reported in IEEE Standard 493-1990, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, 1990, pages 54, 75, 204. This table indicates the % of outages caused by different factors at ORNL and the industry average. The causes are "

Search terms and ID: Cables, Data, Causes, Proceedings, 235

Tortello, 1998

Tortello, Enzo; Bleakley, Graham

“Moving from planned to predictive maintenance,” Modern power systems, 1998, August, 18, 8, 55

Discusses the installation of advanced monitoring systems at power plants and a related switch from planned to predictive maintenance.

Search terms and ID: Generators, Monitoring, Maintenance, Journal Article, 211

Transmission & Distribution, 2000(1)

Transmission & Distribution

“Crises in the making, A,” Transmission & distribution world, 2000, May, NA

Provides numerous comments concerning declining maintenance of the transmission and distribution system and potential problems caused by this trend.

Search terms and ID: System, Causes, Maintenance, Journal Article, 215

Transmission & Distribution, 2000(2)

Transmission & Distribution

"America's aging transmission system," Transmission & distribution world, 2000, May, NA

Presents the opinion that deregulation will lead to the deterioration of the U.S. electric power system.

Search terms and ID: Non-specific, Causes, Journal Article, 216

Verheiden, 1976

Verheiden, E. P.

"Northwest utilities report URD product reliability, 8th Annual, NELPA," Transmission and Distribution, 1976, June, 18-23

Year-end report of underground distribution equipment failures for utilities located in the Pacific Northwest. Author states that the eight culminating years of data can be used to identify time-proven equipment.

Data tables are divided by equipment type. Finish type, total number installed, total and cumulative failures (corrosion, leak and internal) are presented for submersible transformers. Insulation type, miles installed, failures (in 1974) and cumulative failure to date data are presented for primary and low voltage cables. Type, total number, failures (in 1974) and cumulative failure data are also presented for plug-in primary and pole-top terminators and miscellaneous items. The following lists the items for which information is provided. Submersible transformer finishes: Coal Tar, Epoxy, Vinyl, Stainless, Homemade, Direct Buried, Polyester, and Fiberglass. Primary Cable types: HMW PE 175 mil, HMW PE 220 mil, XLPE 175 mil, XLPE 220 mil, XLPE 260 mil, XLPE 295 mil, Butyl-Neoprene, EPR 175 mil, EPR 220 mil, HMWP 260 mil, HMWP 280 mil, HMWP 295 mil, HMWP 345 mil. Low Voltage Cable, Type Insulation: Poly (Sodium), XLP, PVC, and Rubber Neoprene. Plug-in Primary Terminators Types: Non-LB. Rubber, Non L.B.Metal, L.B. Rubber, L.B. Metal. Pole-Top Terminators types: Porcelain Compound, Porcelain Epoxy, Porcelain Elastomer, Molded Rubber, Taped, Scotch 83A3, Porcelain Elastomeric Compound. Miscellaneous Items: Single-Phase Pad Mount Transformers, Three-phase Pad Mount Transformers, UG Street Light Cable, Secondary Connectors, No. 6 Al Duplex Street Light XLPE, Heat Shrink Covers, Insulated Secondary Bus Connectors, Primary Loadbreak Junction Bus, 15-kV 175 mil URD Cable, 600-v URD Triplex, 25-kV Loadbreak Elbows, 25-ky Porcelain Terminator With Elastomer Filler, 15-ky Porcelain Terminator With Elastomer Filler, Loadbreak (2-4 way) Junctions, 15-kV Primary Splices, 15-kV Deadend Cap, Secondary Connections, No. 2 Al Triplex XLPE.

Search terms and ID: System, Data, Report, 108

Verheiden, 1975

Verheiden, Eric P.

"URD Equipment Reliability-NELPA 7th Annual Report," Undergrounding, 1975, January/February, 12-19,44

Annual report presents reliability data for underground distribution equipment in the Pacific Northwest. Only natural failures are included in the report.

Data from the report is split into six groups: submersible transformers, primary cable, low voltage cable, plug in primary terminators, pole top terminators and miscellaneous items. For submersible transformers, data for corrosion and internal failures and average life before failure is presented. Primary cable data include miles installed, failures during the past year, failures to date and average life before failure. Low voltage cable data include thickness, miles installed, failures during the past year, failures to date and average life before failure. Plug in primary terminator; pole top terminator and miscellaneous item data include total number on system, failures during the past year, failures to date and average life before failure. This report also includes Table 7, which presents a summary of reported underground equipment failures on the Montana Power Company system during 1974. Data regarding equipment type, age and cause of failure are presented.

Search terms and ID: System, Data, Causes, Report, 123

Verheiden, 1974

Verheiden, Eric P.

"NELPA 6th Annual Report," Undergrounding, 1974, March/April, 3, 2, 62-67

Annual report presents reliability data for underground distribution equipment in the Pacific Northwest. Only natural failures are included in the report. Report copy is of poor quality.

Data from the report is split into six groups: submersible transformers, primary cable, low voltage cable, plug in primary terminators, pole top terminators and miscellaneous items. For submersible transformers, data for corrosion and internal failures and average life before failure is presented. Primary cable data include miles installed, failures during the past year, failures to date and average life before failure. Low voltage cable data include thickness, miles installed, failures during the past year, failures to date and average life before failure. Plug in primary terminator; pole top terminator and miscellaneous item data include total number on system, failures during the past year, failures to date and average life before failure.

Search terms and ID: System, Data, Causes, Report, 122

Verheiden, 1973

Verheiden, Eric P.

"5th Annual Report: U.R.D. Equipment & Materials Reliability in the Northwest, NELPA," Undergrounding, 1973, January/February, 2, 1, 12-17,30

Annual report presents reliability data for underground distribution equipment in the Pacific Northwest. Only natural failures are included in the report.

Data from the report is split into six groups: submersible transformers, primary cable, low voltage cable, plug in primary terminators, pole top terminators and miscellaneous items. For submersible transformers, data for corrosion and internal failures and average life before failure is presented. Primary cable data include miles installed, failures during the past year, failures to date and average life before failure. Low voltage cable data include thickness, miles installed, failures during the past year, failures to date and average life before failure. Plug in primary terminator; pole top terminator and miscellaneous item data include total number on system, failures during the past year, failures to date and average life before failure.

Search terms and ID: System, Data, Causes, Report, 121

Verheiden, 1972

Verheiden, Eric P.

"U.R.D. Equipment & Materials Reliability in the Northwest, Fourth Annual Report NELPA," Undergrounding, 1972, March/April, 16-23

Annual report presents reliability data for underground distribution equipment in the Pacific Northwest. Only natural failures are included in the report.

Data from the report is split into six groups: submersible transformers, primary cable, low voltage cable, plug in primary terminators, pole top terminators and miscellaneous items. For submersible transformers, data for corrosion and internal failures and average life before failure is presented. Primary cable data include miles installed, failures during the past year, failures to date and average life before failure. Low voltage cable data include thickness, miles installed, failures during the past year, failures to date and average life before failure. Plug in primary terminator; pole top terminator and miscellaneous item data include total number on system, failures during the past year, failures to date and average life before failure.

Search terms and ID: System, Data, Causes, Report, 120

Vermeulen, 1997

Vermeulen, S.T.J.A.; Rijanto, H. ; van der Duyn Schouten, F.A.

"Influence of Preventative Maintenance on the Reliability Performance of Simple Radial Distribution System Parts, The," UPEC 1997, 1997, 1077-1079

Protective system reliability is important in minimizing outages and protecting distribution equipment. A model is presented that purports to evaluate the reliability performance of power systems with multiple components and their protection systems. Because modeling a power system within a single Markov model lends to dealing with a large state space, a method is advocated that combines the results of different Markov models that describe different parts of the system.

Search terms and ID: System, Financial, Technical, Journal Article, 31

Volkmann, 1991

Volkmann, C.A.; Goldberg, S.; Horton, W.F.

"Probabilistic approach to distribution system reliability assessment, A," Third International Conference on Probabilistic Methods Applied to Electric Power Systems, 1991, 169-173, IEE, London, UK

The Pacific Gas and Electric Company (PGE), together with California Polytechnic State University in San Luis Obispo, has developed a personal computer program for evaluating the reliability levels of their electric distribution circuits. The program, called the Distribution Reliability Assessment Model (DREAM), incorporates historical outage information with circuit component failure rates and estimates of fault response and component repair times to compute expected levels of customer outage frequency and duration. The authors highlight recent enhancements to DREAM, which allow for the evaluation of both overhead and underground circuits. The authors also describe their efforts to measure the accuracy of the DREAM calculations and the application of the program in predicting the reliabilities of 180 feeders.

The paper supplies a significant amount of data used by the Dream system on failure rates. The data for underground feeders is not referenced. A table on page 169 supplies failure rates in failures per year (failures/ meter-year for cable) for non-load break elbow, molded splice, transformer, switch, HMWPE cable, XLPE cable, and fuse. A table on 170 provides data for overhead components. This data is based on 85 rural and 95 urban feeders over a period of approximately 5 years. Rural and urban failure rates in failures per year (failures/ meter-year for cable) are provided for conductor, transformer, switch, fuse, capacitor, recloser, and voltage regulator.

The conductor failure rates are for component failures not for failures due to external causes. Adjusted failure rates that include external causes are also provided for conductors, page 170.

On page 171 response or repair times are provided for both rural and urban failures. Data are provided for cable, OH Conductor, molded splice, elbow, capacitor, regulator, OH transformer, UG transformer, OH switch, UG switch, recloser, OH fuse, UG fuse, and external electrical."

Search terms and ID: Multiple, Financial, Data, Proceedings, 240

Walker, 1983

Walker, A.J.

"Degradation of the Reliability of Transmission and Distribution Systems During Construction Outages," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 112-118, IEE, London, United Kingdom

This paper discusses standards regarding thermal capabilities not being exceeded during single or double circuit outages during construction projects. The standards are expressed in terms of the design of the system rather than the risk of loss or the availability of supply to consumers. Furthermore, discusses how reliability data can be used in cost/benefit analyses regarding the degradation of reliability during construction outages.

This article provides fault statistics for active failure rates of switchgear and overhead line faults and provides reliability data for 275kV systems. Active failure rate of 275 kV switchgear is about 0.01 faults per year. 1.5% of all active supergrid overhead line faults - reported over a five-year period- caused simultaneous tripping on double circuit lines. Some comments on overhead line fault data are illegible in our copy.

Search terms and ID: System, Technical, Data, Proceedings, 6

Ward, 2001

Ward, B.; Traub, T.; Alfieri, M.; Bolton, S.; Chu, D.; Hammers, J.

"Integrated Monitoring and Diagnostics: Maintenance Ranking and Diagnostics Algorithms for Transformers," 1001951, 2001, October, EPRI, Palo Alto, California

This report describes algorithms to monitor problems that could potentially develop within power transformers and associated load tap changing and auxiliary equipment. Used in conjunction with EPRI's Maintenance Management Workstation (MMW) or other suitable software, the algorithms can provide prioritized indication and alerts to focus attention on transformer problems before they lead to more extensive damage. The report also provides a concise table that links each parameter that can be measured or monitored to the problem categories and examples. This information can be used by less experienced personnel to understand and respond to off normal conditions of power transformers.

Provides an extensive list of tests and a guide to their purpose, interpretation, and appropriate response. Does not link test results to the probability of failure except in a qualitative manner.

Search terms and ID: Transformers, Monitoring, Report, 267

Wareing, 1998

Wareing, J.B.

“Failure modes in overhead lines,” Colloquium on Distribution overhead lines - economics, practice, and technology of reliability assessment, 1998, 289, 2/1 - 2/10, IEE, London, UK

This report covers failure modes in overhead lines and looks at modes of failure of overhead line conductors, joints and terminations, insulators, pole mounted equipment and support structures under normal 'wear and tear', overloading and adverse weather conditions.

The only data provided are expected lifetimes of several components.

Search terms and ID: Multiple, Causes, Proceedings, 241

Watson, 1981

Watson, W.G.; Walker, A.J.; Fisher, A.G.

“Evaluation of the cost and reliability implications of alternative engineering investment policies for replacement of plant on ageing distribution systems,” International Conference on Electricity Distribution, 1981, 326-30, IEE, London, UK

As a result of the changes in load growth rate in recent years the average age of many distribution systems has been increasing, leading to a growing need for replacement of old distribution plant. The paper describes the development of workload forecasts for the replacement of plant in one Area Board over the next thirty years, and contains examples showing consequences, for performance and cost, of alternative replacement strategies for switchgear in 11 kV urban networks. The performances of these networks are evaluated using a computer program that calculates the principal reliability of supply indices. Cost-benefit assessments are made of the alternative replacement strategies considered.

This report presents interesting data related to aging components. Table 1 presents the expected lives of various distribution components. Max, Min, and Median expected lives in years are presented for 132kV and 33kV underground cables, 11kV paper underground cables, LV lead sheath underground cables, LV aluminum sheath underground cables, overhead copper conductors, overhead aluminum conductors, wood poles, steel towers, 132/33kV and 33/11kV transformers, 11kV/LV ground mounted transformers, 11kV/LV pole mounted transformers, circuit breakers, and oil switches and fuses. Figure 3 plots switchgear age groups against % of equipment experiencing failures and defects. Included are switch fuses defects, circuit breaker failures, mechanisms, and insulation. In addition fault rates per 100km-year and per 100 unit-year for cable, transformer, automatic switch fuse, and feeder sectioning unit. Event durations are for switching operations, travel between substations, operation of oil switch, operation of source circuit breaker, backfeed via LV system, inspection of earth fault indicator, transfer transformer tail at FSU, repair cable, replace transformer, replace switchgear, maintain one substation, maintain two substations, and maintain three substations. Data is drawn from the experience of the Eastern Electricity Board in the UK. In 1980 they had a load of just over 5,000 MW and approximately 50,000 substations.

Search terms and ID: Multiple, Data, Financial, Proceedings, 229

Welch, 2001

Welch, Greg; Willis, H. Lee; Lux, A.

"Prioritizing Operations and maintenance for aging T&D systems workshop," 2001, February 20, EUCI

Reliability centered maintenance is discussed in some detail. It begins by discussing why utilities are under pressure to provide higher reliability at lower cost. It moves on to discuss benefit cost ratios and an RCM based ranking scheme for reliability improvement projects. It provides a simplified example. It ends with recommendations on establishing an RCM based prioritization system.

This presentation has very little data. There is a table for Power Transformers with a note, "Developed for illustrative purposes only. Do not apply to specific maintenance decisions. It lists for various transformer equivalent ages the impact of variance maintenance or refurbishment actions.

Search terms and ID: System, Maintenance, Financial, Proceedings, 223

West, 1997

West, J. Doug

"Approach To Minimize the Maintenance Cost For An Aircraft Electrical Power Generator, An," Unknown, 1997

The paper describes a Type II maintenance policy that uses the non-homogeneous Poisson process (NHPP) with a power law intensity function to describe the failure data and the forward recurrence time. The Type II policy requires that the system be overhauled at the first failure past a pre-specified overhaul interval, and that only minimal repairs are accomplished until this interval is reached.

The contribution of the paper may be summarized as developing the Type II policy for the NHPP process by modifying the existing theory to use the concepts of repairable systems rather than non-repairable ones. The paper derives a cost function, which depends upon the replacement interval T and calculates a replacement time so as to minimize the cost function.

The author first presents a summary of failure models and non-homogeneous Poisson process and continues with the approach of Muth (An Optimal Decision Rule for Repairs vs Replacement, vol. R-26, no. 3, pp. 179-181. August 1977) to derive a cost as a function of overhaul interval. Arguing that Muth's concept of mean residual life time (MRLT) is not defined for repairable systems, the author replaces MRLT with forward recurrence time and calculates this quantity on the basis of the distribution for a specific form of NHPP called power-law process. The same distribution is used to calculate the expected number of failures within the interval of interest. Finally, the author applies the method to minimizing the replacement cost for an aircraft integrated drive generator. Based on this analysis and using two sets of parameter values for the power law process, the paper arrives at overhaul intervals of between 3360 and 7270 flight hours.

Under a Type II maintenance policy, replacement resets age of the system back to 0. Repairs do not change the age of the system. Comparing cost versus overhaul interval is a function of operation time.

Search terms and ID: Other, Technical, Maintenance, Proceedings, 24

Williams, 1983

Williams, W.P.; Mudge, S.G.

"Reliability Assessment of Industrial Power Networks," Third International Conference on Reliability of Power Supply Systems 1983, 1983, September, 107-111, IEE, London, United Kingdom

In industrial networks, it is common for designers to perform multiple studies regarding load flow, stability, etc., but reliability assessments are based largely on experience, which leads to over design. This article discusses expressing reliability in terms of degree of probability. The article contends that a probabilistic approach allows for economic comparisons between alternating networks and differing maintenance and operating practices.

The article includes input data for the probabilistic model that includes reliability indices for circuit breakers, transformers, busbars, and feeder cables for differing network configurations. The article does not site the source of the data. The data is found in Table I components covered include: 33 kV circuit breaker, 33/11 KV transformer, 11 kV circuit-breaker, 11kV busbar, 11 kV incoming cable, 11kV feeder cable (rows). Data provided on each component includes failures per year and repair time in hours (columns). Maintenance data is provided in the same table for 33/11 kV interconnector, 11kV bus-section, 11 kV busbar, 11 kV feeder (rows). The data provided are outages per year and outage time in hours (columns)

Search terms and ID: Multiple, Technical, Data, Journal Article, 5

Willis, 2001(1)

Willis, H. Lee; Welch, Gregory V.; Schrieber, R.R.

"Aging Power Delivery Infrastructures," 2001, Marcel Dekkar, Inc., New York, NY

This book provided mostly qualitative reference and tutorial guide on aging power delivery systems. The book covers planning, engineering, operations and maintenance, and management of aging power systems. The 16 chapters are: 1) Aging Power Delivery Infrastructures; 2) Power Delivery Systems; 3) Customer Demand for Power and Reliability of Service; 4) Power System Reliability and Reliability of Service; 5) Cost and Economic Evaluation; 6) Equipment Inspections, Testing, and Diagnostics; 7) Aging Equipment and Its Impacts; 8) Obsolete System Structures; 9) Traditional Reliability Engineering Tools and Their Limitations; 10) Primary Distribution Planning and Engineering Interactions; 11) Equipment Condition Assessment; 12) Prioritization Methods for O&M; 13) Planning Methods for Aging T&D Infrastructures; 14) Reliability Can Be Planned and Engineered; 15) Strategy, Management and Decision-Making; and 16) Guidelines and Recommendations.

Book is primarily qualitative. Some data is presented, but its background is not clearly stated. Of particular interest is Table 1.3, which presents the percentage breakdown of contributing factors to aging infrastructure problems and Figure 7.5, which displays failure rates of underground cables as a function of age. Section at the end of each chapter may contain several references worth investigating.

Search terms and ID: System, General, Data, Book, 80

Willis, 2001(2)

Willis, H.L.; Brown, R.

"Reliability engineering and differentiated reliability service," 2001, September 11-13, ABB

The document is comprised of the overheads from a three-day course. The topics covered were: overview of reliability engineering, overview of distribution systems, reliability indices, outage data and benchmarking, customer cost of reliability, performance based rates, causes of poor reliability, storms and major events, reliability and the power industry, two Q planning, systems approach, aging infrastructures, aging and its effect on systems, differentiated reliability, reliability modeling, risk analysis, marginal cost/benefit analysis, improving reliability, optimizing reliability, and differentiating reliability. Obviously the course emphasizes breadth over depth on any one subject. In each area, generally typical practices or approaches are contrasted with more modern and recommended approaches.

Limited data is provided. Reliability Modeling, page 21 provides a table of failure rate and mean time to repair for substation equipment including power transformers, circuit breakers, disconnect switches, and air insulated buswork; overhead equipment including transmission lines, distribution lines, switches/fused cutouts, and pole mounted transformers; and underground equipment including cable, pad-mount switches, pad-mount transformers, and cable terminations/joints. Reliability Modeling, page 22 provides three graphs also found in other ABB publications. These are failure rate versus equipment age graphs for 25-kV solid cable, 25-kV paper cable, 15-kV solid cable, 15-kV paper cable, 25-kV solid cable joints, 25-kV paper cable joints, 15-kV solid cable joints, 15-kV paper cable joints, 25-kV paper-solid cable joints, 15-kV paper-solid cable joints, 25-kV pad-mounted transformers, and 15-kV pad-mounted transformers.

Search terms and ID: System, Financial, Data, Presentation, 251

Willis, 1997

Willis, H. L.

"Power distribution planning reference book," 1997, Marcel Dekker, New York, New York

Provides a modern source of information for distribution planners and engineers who must meet demands for ever-greater performance while working in an environment of intense cost containment and regulatory review. Addresses the layout and design of power distribution systems in a comprehensive manner, from subtransmission through the service level. The book emphasizes economy as the primary goal of distribution design, and examines in great detail how distribution systems can be designed to achieve adequate performance and reliability at the lowest possible cost, and how cost interacts with electrical performance, reliability and customer service quality. It reviews traditional approaches to designing each component of the subtransmission and distribution system. It also considers new computerized analysis and optimization methods and current concepts including value-based planning, budget-constrained planning, partial T&D forecasting, multiscenario planning, and deregulated utility planning.

Search terms and ID: System, Financial, Technical, Book, 252

Witt, 1996

Witt, James H.; Galdry, Thomas H.

"Improving Overhaul/Replacement Decisions," PWR 1996 Joint Power Generation Conference, ASME 1996, 1996, 30, 265-275, ASME

A large percentage of generation equipment exhibits reduced reliability characteristics with subsequent overhauls. Using data from boiler recirculation pumps, this article suggests implementing software that analyzes reliability trends to determine the effects of overhauls, replacements or doing nothing on equipment. Overhauls were found to be inducing failure events that had to be absorbed before the benefits of the overhaul could be realized. The effects of overhauls were not consistent and overhauls appeared to be performed too frequently. The article presents the OVERT program, which describes equipment's reliability using Weibull distribution based on failure histories.

Linear regression curves and reverse attribution tests (RAT) and Mann-Whitney tests were performed. Data creates a bathtub curve.

Search terms and ID: Generators, Technical, Data, Journal Article, 28

Xourafas, 1987

Xourafas, C.B; Krishnasamy, S.G.

"Prediction of distribution line service reliability by probability methods," Probabilistic Methods Applied to Electric Power Systems Proceedings of the First International Symposium, 1987, 195-202, Pergamon, Oxford, UK

A computer program based on probabilistic methods of analysis/design has been developed for predicting the mode and probability of failure of tangent pole framings. The results from this program are used to perform failure-mode-effect and criticality analysis (FMECA) at the structural component level, and to predict the customer service reliability.

Table 1.0 presents failure rates for two designs the calculations are site specific and there are no details of the data sources.

Search terms and ID: Poles, Technical, Data, Proceedings, 227

B
EQUIPMENT FAILURE RATE DATABASE

Table B-1
Simple Failure Rates

Equipment Database		**Failure rates**								
Buswork										
	Ref	Mok, 1996								
Busbar	/yr	1.50E-03								
	Ref	Dalabeih, 1995								
132 kV busbars	/yr	1.10E-02								
	Ref	Hale, 2000	Willis, 2001(2) low	Willis, 2001(2)hi gh	Heising, 1974	IEEE, 1974(5)				
Switchgear, bare bus	/yr	1.02E-02	2.00E-03	4.00E-02	6.30E-04	4.40E-04				
	Ref	Hale, 2000	Heising, 1974	IEEE, 1974(5)						
Switchgear, insulated bus	/yr	3.90E-04	1.70E-03	1.27E-03						
	Ref	Hale, 2000								
Bus duct, all types	/yr	3.00E-04								
Cable/conductor										
	Ref	Willis, 2001(2)low	Willis, 2001(2) high	Godfrey, 1996 rural	Godfrey, 1996 urb	Volkmann, 1991rural	Volkmann, 1991urb	Chen, 1995		

Overhead conductor	/yr	3.00E-01	1.80E+00	8.05E-02	8.05E-02	1.22E-02	1.93E-02	9.66E-02		
	Ref	Hale, 2000								
>15kV	/yr	2.17E-02								
	Ref	Hale, 2000	Heising, 1974	Horton, 1991 rural	Horton, 1991 urban	Arceri, 1976				
<15kV	/yr	2.49E-01	7.59E-02	1.22E-02	1.98E-02	2.00E-01				
	Ref	Hale, 2000	Willis, 2001(2) low	Willis, 2001(2) high	Verheiden 1976	Heising, 1974	Arceri, 1976	IEEE, 1974(5)	Chen, 1995	
Underground cable	/yr	3.06E-02	5.00E-02	4.00E-01	8.12E-03	1.17E-03	2.00E-01	3.99E-02	4.83E-02	
	Ref	Verheiden, 1976	Heising, 1974							
Approx 600v solid	/yr	2.19E-03	7.35E-04							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
15kV solid	/yr	6.00E-02	8.00E-02							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
25kV solid	/yr	1.20E-01	4.50E-01							
	Ref	Horton, 1979								

Direct buried Polyethylene (PE)	/yr	2.80E-02								
	Ref	Verheiden, 1976	Volkmann, 1991rural	Volkmann, 1991urb	Goldberg, 1987					
Direct buried HMWPE unjacketed	/yr	7.66E-03	3.34E-02	3.34E-02	5.00E-02					
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb	Verheiden 1976	Volkmann, 1991rural	Volkmann, 1991urb	Goldberg, 1987			
Direct buried XLPE unjacketed	/yr	3.22E-02	4.02E-02	3.80E-03	2.00E-03	2.00E-03	3.00E-03			
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb							
Direct buried TRXLPE-SF-PEEJ	/yr	2.25E-02	3.06E-02							
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb							
In Duct XLPE	/yr	4.02E-02	4.02E-02							
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb							
In Cov. Duct XLPE	/yr	3.70E-02	3.70E-02							
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb							
In C.E. Duct XLPE	/yr	3.22E-02	3.22E-02							
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb							

In C.E. Duct TRXLPE-SF-PEEJ	/yr	2.25E-02	2.25E-02							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
15kV paper	/yr	2.00E-02	6.00E-02							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
25kV paper	/yr	2.00E-02	6.00E-02							
Cable/Conductor Connections										
Overhead										
	Ref	Verheiden, 1976								
Pole top terminators, molded rubber	/yr	5.73E-05								
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
Underground splices/terminations	/yr	1.00E-04	2.00E-03							
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb	Verheiden 1976	Volkmann, 1991rural	Volkmann, 1991urb	Goldberg, 1987	Arceri, 1976	IEEE, 1974(5)	Chen, 1995
Splices	/yr	1.00E-03	1.00E-03	2.10E-03	1.90E-04	1.90E-04	6.00E-04	1.00E-03	9.10E-04	6.00E-04

	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
15kV Solid splice	/yr	1.80E-01	8.00E-01							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
25-kV Solid splice	/yr	1.80E-01	8.80E-01							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
15kV Paper-Solid splice	/yr	8.00E-02	2.00E-01							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
25kV Paper-Solid splice	/yr	1.00E-01	3.50E-01							
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
25kV/15kV Paper splice	/yr	4.00E-02	1.20E-01							
	Ref	Goldberg, 1987	Chen, 1995							
Elbows	/yr	6.00E-04	6.00E-04							
	Ref	Hale, 2000	Godfrey, 1996 rural	Godfrey, 1996 urb	Verheiden 1976					
Loadbreak elbows/terminators	/yr	3.70E-04	1.50E-03	1.50E-03	2.63E-04					

	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb	Verheiden , 1976	Volkmann, 1991rural	Volkmann, 1991urb	Arceri, 1976			
Non-loadbreak elbows/terminators	/yr	1.00E-03	1.00E-03	2.83E-04	1.90E-04	1.90E-04	6.00E-04			
	Ref	Verheiden, 1976								
15-kV deadend cap	/yr	3.00E-03								
	Ref	Hale, 2000	Volkmann, 1991rural	Volkmann, 1991urba	Horton, 1991 rural	Horton, 1991 urban				
Capacitor Banks	/yr	1.74E-01	1.05E-02	8.50E-03	1.05E-02	8.50E-03				
Poles										
	Ref	Stillman, 1994								
Wooden	/yr	3.34E-05								
	Ref	Stillman, 1994								
Concrete	/yr	0.00E-00								
	Ref									
Switches/Circuit breakers/fuses	/yr									
	Ref	Chen, 1995								

Switches	/yr	4.00E-03								
	Ref	Hale, 2000	Willis, 2001(2) low	Willis, 2001(2) high	Heising, 1974	IEEE, 1974(5)				
Substation disconnect switches	/yr	1.50E-04	4.00E-03	1.60E-01	6.10E-03	5.42E-03				
0	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Godfrey, 1996 rural	Godfrey, 1996 urb	Volkmann, 1991rural	Volkmann, 1991urb	Horton, 1991 rural	Horton, 1991 urban	
Overhead switches	/yr	4.00E-03	1.40E-02	1.00E-03	1.00E-03	1.26E-03	7.75E-04	1.26E-03	7.75E-04	
	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Volkmann, 1991rural	Volkmann, 1991urb	Goldberg, 1987				
Underground pad mount switches	/yr	1.00E-03	1.00E-02	4.00E-03	4.00E-03	4.00E-03				
	Ref	Hale, 2000								
Automatic transfer	/yr	5.12E-02								
	Ref	Hale, 2000								
Manual transfer	/yr	8.70E-04								
	Ref	Hale, 2000								
Oil filled, >5kV	/yr	1.76E-03								
	Ref	Hale, 2000								
Static	/yr	2.25E-03								

	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Mok, 1996	IEEE, 1974(5)	Degen, 1995				
Circuit breakers	/yr	3.00E-03	2.00E-02	3.00E-03	3.40E-03	6.72E-03				
	Ref	Hale, 2000								
< 600V	/yr	6.40E-04								
	Ref	Steed, 1986								
11 kV	/yr	2.00E-04								
	Ref	Fletcher, 1995								
63-100kV	/yr	2.80E-03								
	Ref	Dalabeih, 1995								
132 kV	/yr	3.60E-02								
	Ref	Hale, 2000	Heising, 1974							
Circuit breaker 3 Phase, fixed	/yr	0.00E+00	5.20E-03							
	Ref	Hale, 2000	Heising, 1974							
Circuit breaker Drawout	/yr	1.11E-03	3.00E-03							
	Ref	Hale, 2000								
Circuit breaker vacuum	/yr	2.01E-02								

	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb	Volkmann, 1991rural	Volkmann, 1991urb	Horton, 1991 rural	Horton, 1991 urban	Chen, 1995		
Recloser	/yr	1.50E-02	1.50E-02	1.50E-02	1.44E-02	1.50E-03	1.44E-03	5.00E-03		
	Ref	Chen, 1995								
Fuses	/yr	3.70E-03								
	Ref	Hale, 2000	Godfrey, 1996 rural	Godfrey, 1996 urb	Volkmann, 1991rural	Volkmann, 1991urb	Mok, 1996	Horton, 1991 rural	Horton, 1991 urban	
Overhead	/yr	8.70E-04	3.00E-03	3.00E-03	4.50E-03	3.74E-03	2.00E-03	4.50E-03	3.74E-03	
	Ref	Hale, 2000	Volkmann, 1991rural							
Underground	/yr	8.70E-04	4.00E-03							
	Ref	Goldberg, 1987	Mok, 1996	Chen, 1995						
Transformers	/yr	2.00E-03	1.50E-02	2.00E-03						
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
Substation power transformers	/yr	1.50E-02	7.00E-02							
	Ref	Dalabeih, 1995								

132/33kV transformer	/yr	1.50E-02								
	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Godfrey, 1996 rural	Godfrey, 1996 urb	Volkmann, 1991rural	Horton, 1991 rural	Horton, 1991 urban	Arceri, 1976	
Overhead Pole mounted	/yr	1.00E-03	4.00E-03	3.00E-03	5.00E-03	2.71E-04	2.71E-04	6.14E-04	4.40E-03	
	Ref	Freeman, 1996								
11kV/415V pole mounted	/yr	1.60E-05								
	Ref	Hale, 2000	Willis, 2001(2) low	Willis, 2001(2) high	Godfrey, 1996 rural	Godfrey, 1996 urb	Volkmann, 1991rural	Heising, 1974	IEEE, 1974(5)	
Pad-mounted	/yr	2.89E-03	2.00E-03	3.00E-03	2.00E-03	3.00E-03	2.30E-03	4.10E-03	4.73E-03	
	Ref	Heising, 1974								
601v-15kV	/yr	3.00E-03								
	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Heising, 1974						
15kV	/yr	7.00E-03	4.50E-02	1.30E-02						
	Ref	Willis, 2001(2) low	Willis, 2001(2) high							
25kV	/yr	1.20E-02	3.20E-02							

	Ref	Verheiden, 1976	Arceri, 1976							
3 phase	/yr	6.21E-03	6.20E-03							
	Ref	Verheiden, 1976	Arceri, 1976							
1 phase	/yr	3.63E-03	4.00E-03							
	Ref	Hale, 2000								
Forced air	/yr	1.08E-02								
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urb	Verheiden 1976						
Submersible	/yr	3.00E-03	3.00E-03	3.08E-03						
	Ref	Verheiden, 1976								
Vinyl	/yr	2.49E-03								
	Ref	Verheiden, 1976								
Stainless	/yr	1.38E-03								
	Ref	Arceri, 1976								
1 phase below grade	/yr	3.80E-03								
Other										
	Ref	Hale, 2000	Godfrey, 1996 rural	Godfrey, 1996 urb	Arceri, 1976					
Arrester, lightning	/yr	1.32E-03	2.00E-04	2.00E-04	2.00E-04					

	Ref	Hale, 2000								
Battery	/yr	7.02E-03								
	Ref	Hale, 2000								
Inverters, all types	/yr	4.82E-03								
	Ref	Hale, 2000								
Meter, electric	/yr	3.60E-04								
	Ref	Hale, 2000	Heising, 1974							
Rectifiers, all types	/yr	4.47E-03	2.98E-02							
	Ref	Verheiden, 1976								
Secondary connectors	/yr	7.81E-05								
	Ref	Hale, 2000								
UPS	/yr	9.20E-04								
	Ref	Hale, 2000	Volkmann, 1991rural	Volkmann, 1991urb	Horton, 1991 rural	Horton, 1991 urban				
Voltage Regulator, static;	/yr	3.63E-02	2.88E-02	2.88E-02	2.88E-02	2.88E-02				

Table B-2
Repair Times

Equipment Database		**Repair times in hours**					
Buswork	Ref	Mok, 1996					
Busbar	Hours	3.5					
	Ref	Dalabeih, 1995					
132 kV busbars	Hours	2.5					
	Ref	Hale, 2000	Heising, 1974				
Switchgear, bare bus	Hours	27.3	17.3				
	Ref	Heising, 1974.0					
Switchgear, insulated bus	Hours	261.0					

Cable/conductor							
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urban	Chen, 1995			
Overhead conductor	hours	3.0	2.5	1.5			
	Ref	Hale, 2000					
>15kV	hours	2.5					
	Ref	Hale, 2000	Heising, 1974				
<15kV	hours	1.8	31.6				
	Ref	Goldberg, 1987	Willis, 2001(2) low	Willis, 2001(2) high	Hale, 2000	Chen, 1995	Heising, 1974
Underground cable	hours	1.5	3.0	30.0	6.8	2.3	95.5
	Ref	Goldberg, 1987	Volkmann, 1991rural	Volkmann, 1991urban			
Direct buried HMWPE unjacketed	hours	1.5	6.0	4.8			

	Ref	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban		
Direct buried XLPE unjacketed	hours	6.0	4.8	10.0	9.5		
	Ref	Godfrey, 1996 urban					
Direct buried TRXLPE-SF-PEEJ	hours	9.5					
	Ref	Godfrey, 1996 urban					
In Duct XLPE	hours	7.5					
	Ref	Godfrey, 1996 urban					
In Cov. Duct XLPE	hours	7.5					
	Ref	Godfrey, 1996 urban					
In C.E. Duct XLPE	hours	5.5					

	Ref	Godfrey, 1996 urban					
In C.E. Duct TRXLPE-SF-PEEJ	hours	5.5					
Cable/Conductor Connections							
Overhead							
	Ref						
Pole top terminators, molded rubber	hours						
	Ref	Willis, 2001(2) low	Willis, 2001(2) high				
Underground splices/terminations	hours	2.0	4.0				
	Ref	Goldberg, 1987	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban	Chen, 1995
Splices	hours	1.5	6.0	4.4	5.5	5.5	3.5

	Ref	Goldberg, 1987	Chen, 1995				
Elbows	hours	3.5	1.7				
	Ref	Hale, 2000	Godfrey, 1996 rural	Godfrey, 1996 urban			
Loadbreak elbows/terminators	hours	0.8	5.5	5.5			
	Ref	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban		
Non-loadbreak elbows/terminators	hours	4.5	4.5	5.5	5.5		
	Ref	Hale, 2000	Volkmann, 1991rural	Volkmann, 1991urban			
Capacitor Banks	hours	2.3	2.3	2.4			

Switches/Circuit breakers/fuses							
	Ref	Chen, 1995					
Switches	hours	1.0					
	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Heising, 1974			
Substation disconnect switches	hours	1.5	12.0	3.6			
0	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban
Overhead switches	hours	1.0	4.0	2.6	2.9	5.5	5.5
	Ref	Goldberg, 1987	Willis, 2001(2) low	Willis, 2001(2) high	Volkmann, 1991rural	Volkmann, 1991urban	
Underground pad mount switches	hours	1.5	1.0	5.0	2.3	4.8	

	Ref	Hale, 2000					
Automatic transfer	hours	4.1					
	Ref	Hale, 2000					
Static	hours	13.0					
	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Mok, 1996	Godfrey, 1996 rural	Godfrey, 1996 urban	
Circuit breakers	hours	6.0	80.0	4.0	17.0	17.0	
	Ref	Hale, 2000					
< 600V	hours	1.0					
	Ref	Dalabeih, 1995					
132 kV	hours	2.0					
	Ref	Heising, 1974					
Circuit breaker 3 Phase, fixed	hours	5.8					
	Ref	Hale, 2000	Heising, 1974				
Circuit breaker Drawout	hours	3.1	129				
	Ref	Hale, 2000					
Circuit breaker vacuum	hours	10.7					
	Ref	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban	Chen, 1995	

Recloser	hours	4.3	2.2	4.0	4.0	1.5	
	Ref	Chen, 1995					
Fuses	hours	1.0					
	Ref	Mok, 1996	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban	
Overhead	hours	1.8	3.6	3.2	2.0	2.0	
	Ref	Volkmann, 1991rural	Volkmann, 1991urban				
Underground	hours	4.3	2.2				
	Ref	Goldberg, 1987	Mok, 1996	Chen, 1995			
Transformers	hours	5.5	10.0	2.5			
	Ref	Willis, 2001(2) low	Willis, 2001(2) high				
Substation power transformers	hours	15.0	480.0				
	Ref	Dalabeih, 1995					
132/33kV transformer	hours	2.0					
	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban
Overhead Pole mounted	hours	3.0	8.0	4.0	5.0	3.5	3.0

	Ref	Willis, 2001(2) low	Willis, 2001(2) high	Volkmann, 1991rural	Volkmann, 1991urban	Godfrey, 1996 rural	Godfrey, 1996 urban
Pad-mounted	hours	2.0	6.0	7.0	5.3	3.5	3.0
	Ref	Heising, 1974					
601v-15kV	hours	174					
	Ref	Hale, 2000					
Forced air	hours	132.4					
	Ref	Godfrey, 1996 rural	Godfrey, 1996 urban				
Submersible	hours	3.5	3.0				
Other							
	Ref	Hale, 2000	Godfrey, 1996 rural	Godfrey, 1996 urban			
Arrester, lightning	hours	4.0	2.0	2.0			
	Ref	Hale, 2000					
Inverters, all types	hours	26.0					
	Ref	Hale, 2000					
Meter, electric	hours	1.0					
	Ref	Hale, 2000	Heising, 1974				
Rectifiers, all types	hours	16.0	380				
	Ref	Hale, 2000	Heising, 1974				
Voltage Regulator, static;	hours	74.8	2.8	2.0			

Table B-3
Aging Data

Equipment Database		**Aging Data**			
	Source	lambda10	lambda20	lambda30	Notes
Buswork					
Cable/conductor					
Overhead conductor					
<15kV	Godfrey, 1996	8.05E-02	8.81E-02	9.30E-02	Based on Weibull distribution and 10th year and terminal year rates
<15kV	Godfrey, 1996	3.22E-02	4.16E-02	4.83E-02	Based on Weibull distribution and 10th year and terminal year rates
Underground cable	Medek, 1989	2.50E-03	3.40E-02	1.40E-01	Report stated that failures were approximated by a Iowa S3 statistical normal curve with a mean of 28 years. The best references I could find on this was that 3/4 of the assets would die within 30% of the mean. That is approximated by a normal with mean 28 and sd of 7.25.
Underground cable	Dedman, 1990	4.32E-02	6.94E-02	9.15E-02	I fitted a Weibull distribution to the failure data that they supplied by year of installation
15kV solid	Willis, 2001(2)	6.00E-02	7.00E-02	8.00E-02	Read from an ABB graph
25kV solid	Willis, 2001(2)	1.20E-01	2.80E-01	4.50E-01	Read from an ABB graph
Direct buried Polyethylene (PE)	Horton, 1979	2.80E-02	5.63E-02	8.51E-02	Calculated based on F(t) the cumulative failure function defined as (k/(n+1))*t^(n+1). Used .01 miles as the unit.

Direct buried HMWPE unjacketed	Horton, 1991(1)	1.40E-02	2.10E-02	3.10E-02	Calculated based on a failure rate of the form f(t)=Kt^n, w. K=.65 and n=0.3
Direct buried XLPE unjacketed	Horton, 1991(1)	1.30E-03	1.30E-03	1.40E-03	Calculated based on a failure rate of the form f(t)=Kt^n, w. K=.13 and n=0
Direct buried XLPE unjacketed	Horton, 1991(1)	4.70E-03	4.90E-03	5.20E-03	Calculated based on a failure rate of the form f(t)=Kt^n, w. K=.45 and n=0
Direct buried XLPE unjacketed	Godfrey, 1996	3.22E-02	6.44E-02	9.66E-02	Based on Weibull distribution and 10th year and terminal year rates
Direct buried XLPE unjacketed	Godfrey, 1996	4.02E-02	8.05E-02	1.21E-01	Based on Weibull distribution and 10th year and terminal year rates
Direct buried XLPE unjacketed	Horton, 1979	6.00E-03	1.20E-02	1.80E-02	Calculated based on F(t) the cumulative failure function defined as (k/(n+1))*t^(n+1). Used .01 miles as the unit.
Direct buried TRXLPE-SF-PEEJ	Godfrey, 1996	2.25E-02	4.56E-02	6.88E-02	Based on Weibull distribution and 10th year and terminal year rates
Direct buried TRXLPE-SF-PEEJ	Godfrey, 1996	3.06E-02	5.63E-02	8.05E-02	Based on Weibull distribution and 10th year and terminal year rates
In Duct XLPE	Godfrey, 1996	4.02E-02	8.05E-02	1.21E-01	Based on Weibull distribution and 10th year and terminal year rates
In Cov. Duct XLPE	Godfrey, 1996	3.70E-02	7.33E-02	1.09E-01	Based on Weibull distribution and 10th year and terminal year rates
In C.E. Duct XLPE	Godfrey, 1996	3.22E-02	6.44E-02	9.66E-02	Based on Weibull distribution and 10th year and terminal year rates
In C.E. Duct TRXLPE-SF-PEEJ	Godfrey, 1996	2.25E-02	4.56E-02	6.88E-02	Based on Weibull distribution and 10th year and terminal year rates
15kV paper	Willis, 2001(2)	2.00E-02	4.00E-02	6.00E-02	Read from an ABB graph

25kV paper	Willis, 2001(2)	2.00E-02	4.00E-02	6.00E-02	Read from an ABB graph
Cable/Conductor Connections					
Overhead					
Underground splices/terminations					
Splices	Godfrey, 1996	1.00E-03	1.00E-03	1.00E-03	Based on Weibull distribution and 10th year and terminal year rates
15kV Solid splice	Willis, 2001(2)	1.80E-01	4.60E-01	8.00E-01	Read from an ABB graph
25-kV Solid splice	Willis, 2001(2)	1.80E-01	5.30E-01	8.80E-01	Read from an ABB graph
15kV Paper-Solid splice	Willis, 2001(2)	8.00E-02	1.50E-01	2.00E-01	Read from an ABB graph
25kV Paper-Solid splice	Willis, 2001(2)	1.00E-01	2.30E-01	3.50E-01	Read from an ABB graph
25kV/15kV Paper splice	Willis, 2001(2)	4.00E-02	8.00E-02	1.20E-01	Read from an ABB graph
Elbows					
Loadbreak elbows/terminators	Horton, 1991(1)	9.00E-04	1.80E-03	3.60E-03	Calculated based on a failure rate of the form f(t)=Kt^n, w. K=.00009 and n=1
Loadbreak elbows/terminators	Godfrey, 1996	1.50E-03	2.00E-03	2.37E-03	Based on Weibull distribution and 10th year and terminal year rates
Non-loadbreak elbows/terminators	Godfrey, 1996	1.00E-03	1.00E-03	1.00E-03	Based on Weibull distribution and 10th year and terminal year rates

Capacitor Banks	Faraq, 1999	2.50E-02	7.07E-02	1.30E-01	Calculated based Weibull with Alpha 25.13 and Beta 2.5
Capacitor Banks	Faraq, 1999	1.94E-01	1.91E+00	7.27E+00	Calculated based Weibull with Alpha 12.04 and Beta 4.3
Poles					
Wooden	Stillman, 1994	3.34E-05	3.01E-04	1.09E-03	Based on three parameter Weibul Alpha=96, Beta=4.17, gamma=0
Wooden	Stillman, 1994	3.11E-04	5.42E-03	2.04E-02	Based on three parameter Weibul Alpha=43, Beta=3.6, gamma=5
Concrete	Stillman, 1994	0.00E+00	0.00E+00	2.37E-05	Based on three parameter Weibul Alpha=114, Beta=4, gamma=20
Switches/Circuit breakers/fuses					
Switches	Steed, 1986	1.80E-04	3.00E-04	5.00E-04	Read from graph, this is for 11kV and includes all components such as cable boxes and busbar joints
Overhead switches	Watson, 1981	5.00E-04	2.10E-03	2.70E-03	Read from graph with extrapolation from 25 to 30 years
Overhead switches	Godfrey, 1996	1.00E-03	1.00E-03	1.00E-03	Based on Weibull distribution and 10th year and terminal year rates
Circuit breakers	Watson, 1981	1.50E-03	1.00E-03	7.00E-04	Read from graph. Note that the failure increases significantly beyond 35 years.
Circuit breakers	Godfrey, 1996	9.00E-02	9.95E-02	1.06E-01	Based on Weibull distribution and 10th year and terminal year rates

11 kV	Steed, 1986	2.00E-04	4.30E-04	1.10E-03	Read from graph
Recloser	Godfrey, 1996	1.50E-02	1.73E-02	1.88E-02	Based on Weibull distribution and 10th year and terminal year rates
Fuses					
Overhead	Godfrey, 1996	3.00E-03	3.00E-03	3.00E-03	Based on Weibull distribution and 10th year and terminal year rates
Transformers					
Substation power transformers					
Overhead Pole mounted	Godfrey, 1996	3.00E-03	3.87E-03	4.50E-03	Based on Weibull distribution and 10th year and terminal year rates
Overhead Pole mounted	Godfrey, 1996	5.00E-03	5.92E-03	6.53E-03	Based on Weibull distribution and 10th year and terminal year rates
Overhead Pole mounted	Steed, 1986	1.10E-05	4.90E-05	1.70E-04	Read from hazard rate graph
11kV/415V pole mounted	Freeman, 1996	1.60E-05	1.15E-04	8.09E-04	Based on a Gumbel distribution fitted to data from 181,000 UK transformers
Pad-mounted	Godfrey, 1996	2.00E-03	2.83E-03	3.46E-03	Based on Weibull distribution and 10th year and terminal year rates
Pad-mounted	Godfrey, 1996	3.00E-03	3.87E-03	4.50E-03	Based on Weibull distribution and 10th year and terminal year rates
Pad-mounted	Steed, 1986	1.00E-06	1.50E-05	1.25E-04	Read from hazard rate graph

15kV	Willis, 2001(2)	7.00E-03	4.50E-02	1.50E-01	Read from an ABB graph
15kV	Horton, 1991(1)	3.10E-03	3.20E-03	3.30E-03	Calculated based on a failure rate of the form f(t)=Kt^n, w. K=.003 and n=0
25kV	Willis, 2001(2)	1.20E-02	3.20E-02	6.00E-02	Read from an ABB graph
Submersible	Godfrey, 1996	3.00E-03	3.87E-03	4.50E-03	Based on Weibull distribution and 10th year and terminal year rates
Submersible	Godfrey, 1996	3.00E-03	3.87E-03	4.50E-03	Based on Weibull distribution and 10th year and terminal year rates
Other					
Arrester, lightning	Godfrey, 1996	2.00E-04	3.87E-04	5.70E-04	Based on Weibull distribution and 10th year and terminal year rates

Target:
Distribution Systems

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