Managing Aging Distribution System Assets

Research Status Report

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ABSTRACT

This report 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 service. 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 an 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 we are developing seek an optimal (least-cost) policy for maintenance and replacement of electric distribution assets.

CONTENTS

1 INTRODUCTION

The purpose of this report is to describe and evaluate what is known with respect to the analysis of the problem of aging assets in electric distribution systems. The problem of how best to manage aging assets has been studied for many years by many researchers. We seek methods to analyze the problem with particular attention to the specific issues of electric distribution systems, where assets have been in place for long periods, subject to random shocks and other conditions, and have been maintained in varying ways depending upon the practices of the utility.

We are particularly interested in identifying and developing appropriate methods and sources of data to serve as inputs to appropriate methods.

This report presents a progress report on the result of our efforts to date. We began this project with a literature survey to learn what is currently known with respect to managing aging assets. Three fundamental issues with respect to this problem guided the literature search.

- First, what methods are available to apply to the problem? This is an issue of models and problem formulation.
- Second, what data is available to serve as inputs to the methods? This is an issue of utility experience and whether that experience has been captured in some accessible form.
- Third, what has been implemented in usable form to solve this problem? This is an issue of commercially available software implementations.

The objective of this research is to assemble data and methods to aid the development of least-cost maintenance and replacement policies for specific classes of electric distribution assets. The classes of assets include such things as transformers, breakers and conductors.

1.1 Methods

The problem of selecting methods for managing aging assets requires consideration of three distinct phenomena. The first consideration is how best to represent the dynamic processes of failure and repair of equipment. The second consideration is how to modify the failure and repair processes to account for aging of equipment. The third consideration is how to combine the economics of failure and repair of equipment with the economics and constraints of utility service to customers. Any successful method must address all these considerations.

1.1.1 Failure and Repair

The methods for analysis of failure and repair of equipment are well known. We addressed the methodology issue in our report *Reliability of Electric Utility Distribution Systems: EPRI White Paper (1000424).* The most popular models in the literature represent the failure and repair of equipment as a Markov process. These Markov models provide a useful perspective on the key issues, so we will provide a brief summary here.

The Markov process identifies various *states* (e.g., “up”, “down”) that characterize the condition of equipment. The transitions from state to state are governed by probability distributions. The typical assumptions made include specification of constant transition rates. This defines a *stationary* Markov model, the solution of which, for an arbitrary number of states, is well understood (Barlow (1965), Billinton (1983)).

An essential idea underlying the applicability of the stationary Markov model is the assumption that the *hazard rate* is constant. The *reliability* of an asset is defined as the probability that it survives (does not fail) at least up until some arbitrary time. The hazard rate is the conditional probability that the asset fails in the next instant of time given that it survived until the present.

The concept of the hazard rate is interesting for several reasons. First, the hazard rate can be empirically observed and is most often expressed as a so-called *bathtub curve.* (See figure 1-1.) The nature of the hazard rate is that it tends to start out relatively large and decrease, during the *burn-in* period, remain constant for an arbitrary time, during the *steady-state* period, and then increase, during the *burn-out* period. Second, the burn-out period reflects the effect of aging. Hence, we are motivated to consider the behavior of the hazard rate as a fundamental modeling issue for the study of aging assets. Third, the stationary Markov model applies in the steady-state period, since the hazard rate is constant, reliability is exponential, and the reciprocal of the hazard rate is the mean time to failure. It is important to note that these specifications are generally not valid for aging distribution assets.

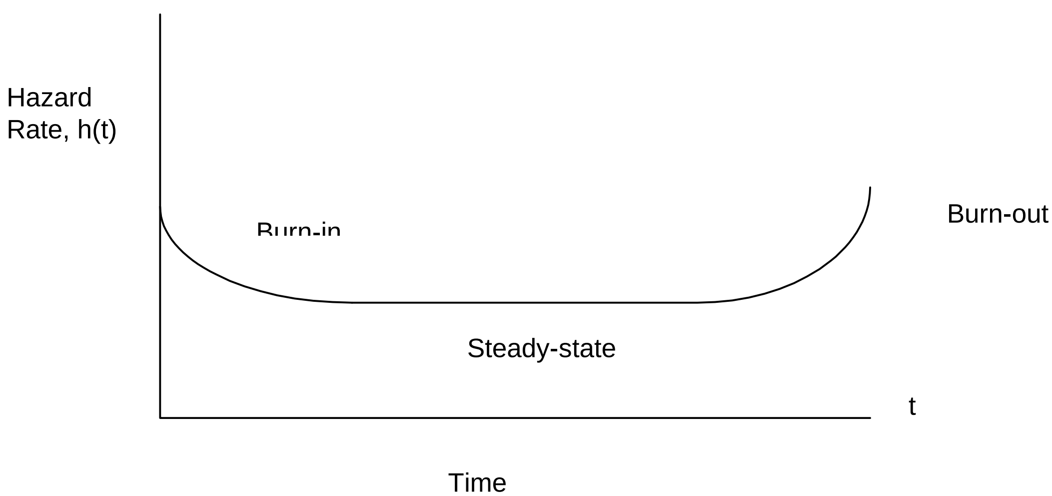

Figure 1-1
Hazard Rate “Bathtub” Curve

For aging assets, it is natural to address the effect of hazard rate directly. We will be exploring a nonstationary Markov approach that permits variable transition rates. We will present a method in Chapter 4 that develops nonstationary hazard rates directly, as a function of age and current state. That joint dependence appears to be fundamental to capturing failure and repair of aging assets, and combines the increasing hazard rate and Markov modeling concepts.

1.1.2 Equipment Aging

One aspect of the phenomenon of equipment aging was discussed above. That is, the burn-out period associated with aging indicates that as an asset ages it is not appropriate to apply stationary failure probabilities to represent failure dynamics. Other considerations are important to address as well. These include derating, quality of service, and technological change.

As equipment ages, it is important to determine whether the older equipment can perform the function for which it was originally installed. Performance is often measured with respect to capacity (MW), the transmission or distribution peak capability. It is natural to expect that aging may reduce this capability, hence aging suggests the need to derate the capacity of an asset.

Quality of service is becoming a more important issue than it had been in the past. It is possible that aging may interfere with the ability of an asset to provide service at the quality intended. This concept is perhaps somewhat less precise than derating. Nevertheless, deterioration with respect to quality may be an important phenomenon to consider. We will need to discover or create methods to address this issue. We are searching the literature for any indication that other researchers have addressed this issue.

Technological change is a classic consideration in the analysis of replacement of aging assets (Bellman (1955)). Technological change entails several phenomena related to aging. First, as technology improves, the benefit of replacing an aging asset that embodies the older, presumably inferior, technology by a new, superior asset increases. Second, technological change may offer improved operating techniques that may increase the future value of an aging asset. Third, the salvage or trade-in value of an aging asset tends to decrease more rapidly than otherwise as the technology improves.

1.1.3 Economic Considerations

It is natural to formulate the problem of managing aging assets as a cost minimization problem, assuming that the asset is constrained to provide a fixed level of service. In addition to the costs of failure and repair, the problem of managing aging assets suggests consideration of other costs, including (a) operating and maintenance costs, (b) salvage value, (c) lost revenue due to deteriorating quality or derating, and (d) replacement costs. Each of these costs must be represented in the analysis of aging assets. At minimum, the representation of such costs should include considerations of calendar time, which permits modeling the effect of technological change or other kinds of learning, as well as the dependence of costs upon the so-called *vintage* or age of an asset.

Operating and maintenance costs tend to increase as an asset ages (i.e., cost is an increasing function of vintage). In addition, the qualitative nature of the maintenance performed may change as an asset ages. Further, the consequences of various maintenance policies may differ as technology changes, since technological improvements can enhance the effect of maintenance. It is reasonable to suppose that there are differing economic consequences of alternative maintenance policies. These differences must be captured in an appropriate analysis method.

Salvage value measures the worth of an asset when it is retired from service. Salvage value tends to be a decreasing function of vintage. The rate of decrease can be accelerated as technological improvement occurs. Clearly, optimal replacement time depends on how rapidly the value of an asset depreciates.

It may be important to measure the consequences of aging by assessing the losses in revenue associated with deteriorating quality or derating. As the aging asset performs less well, costs may accrue. Such costs might include performance penalties or additional expenses the utility must incur as the aging asset remains in operation. We will search for further characterization of these costs in the literature and in our interviews.

Replacement costs are an important consideration in management of aging assets. As technology changes, replacement costs will also change, although the direction of such changes may be uncertain. Such uncertainty is clearly an important consideration in the management of aging assets. The standard approaches to the problem tend to treat replacement costs as relatively deterministic. This may not be sufficient in the present environment. If uncertainty in replacement costs is an important consideration, then the methodology must be designed so that uncertainty can be assessed and the corresponding consequences for replacement decisions explored.

1.2 Data

At this time, we cannot describe sources of data with great precision. It is interesting to note that even in the small sample survey results we have observed (see Appendix A), there is great uncertainty about many of the important descriptors of the aging asset problem.

We are guided by two fundamental concepts about data. First, analytic methods should strive to replace exhaustive data sets with analysis. This is one of the defining characteristics of the Area Investment Strategy Model that was developed for policy analysis of distribution system capacity expansion. Many alternate approaches rely on statistical analyses of vast databases. But the most successful approaches substitute structure for data and allow logic to identify best policies.

Second, we believe that methodological considerations and data requirements are linked. Indeed, we recognize that the appropriate data to collect is a direct consequence of the design of the methodology that will use the data. To be sure, there is an important feedback loop in the linkage, such that the methodology must be designed subject to availability of data. Nevertheless, unless it is infeasible to collect the required information, the best approaches begin with a methodology that captures problem understanding and then use this methodology to drive the data collection.

The basic idea here is that modeling logic and analysis should be used to establish the scope of the data gathering. It is often the case that the modeling logic implies that precise measurement of many data elements is not necessary for decision making. In practice, we consider methodology design and data availability simultaneously. An interesting outcome of this research may be to guide data collection, assuming that current data is insufficient to serve as a complete set of inputs for the proposed methodology.

1.3 Implementations

There is extensive literature and expertise concerning the mathematical formulation of the repair / replace policy problem. We are searching for implementations (commercially available software packages) of solution methods for the aging assets problem. It is almost certain that none exists, but that remains to be seen. (As of this writing, none has been identified.)

There are two requirements for implementation. First is the requirement for software that will identify least-cost repair / replace policies given inputs that include policy alternatives, costs and equipment performance probabilities. Once the specific electric distribution aging asset problem is understood, mathematical and software implementation should be straightforward. The second requirement for implementation is for failure mode models that can provide inputs to the policy analysis. The failure mode models should characterize the likelihood of failure of key equipment conditional on age and other factors. (EPRI is currently working with equipment experts and the electric industry to formulate such models.)

Regarding the software requirement, any implementation will be based on a mathematical formulation that itself is based on an optimization technique. There are several mathematical optimization techniques that could be appropriate for this problem. The appropriate techniques include optimal control (applying the Pontryagin maximum principle) (Ahmed (1978), Kamien (1971)), deterministic dynamic programming (Bellman (1955)), nonlinear programming (Inagaki (1978)), and stochastic dynamic programming (Hillier (1986)). Perhaps the most natural approach is stochastic dynamic programming. We describe the development and implementation of such a model in Chapter 4.

1.4 Description Of Report

This report contains four additional chapters and two appendices. In Chapter 2, we discuss the literature survey and summarize, in some detail, the publications studied to date. The literature survey is ongoing. In Chapter 3, we review some of the most popular and accessible methods of analysis that have been applied to the problem of aging assets, including (a) the *classical engineering economics formulation*, which models deterministic cash flows; (b) the *dynamic programming formulation*, which permits analysis over a finite planning period for a more sophisticated set of alternatives; and (c) the *network formulation*, which is natural and simple, and applies linear programming. We offer a critique of these methods and explain why they are insufficient for the problem of aging assets as we think about it. In Chapter 4, we describe a real utility problem, aging air breakers, and formulate it using stochastic dynamic programming. We present a simple solution to the problem in that chapter. Chapter 5 is a brief statement of our current conclusions and an outline of how we propose to continue this research. Appendix A presents the questionnaire we distributed to utility advisers and contains a table that summarizes the results of the questionnaire. The references consulted in preparing this report are listed in Appendix B.

2
LITERATURE REVIEW

The literature discussing aging assets is vast. A survey paper published nearly twenty years ago (Sherif (1981)) listed 524 citations. We have not yet found a more recent comprehensive survey. Nevertheless, we have identified many interesting scholarly and practical papers. The documents we have found are listed in the references section, Appendix B, below.

Several documents have been reviewed as part of our continuing research efforts. Discussions of these documents are provided in this chapter. The documents are listed alphabetically by author.

We are searching for, among other things, descriptions of methodology for analysis of aging assets, discussions of conditions met in electric distribution systems, sources of data for aging assets analysis, and the description and consequences of various policies with respect to aging assets, such as derating. The literature review is an ongoing effort. We report progress to date.

2.1 Summary Of Documents Reviewed

R. N. Allan and R. Billinton (1995). Concepts of Data for Assessing the Reliability of Transmission and Distribution Equipment

The paper addresses the issues relating to the reliability of the equipment in transmission and distribution systems. The benefit of addressing these issues is to improve the effectiveness and efficiency of managing the system and its assets in order to meet customers' requirements of a reliable power supply constrained by the cost of achieving these requirements. Among these issues are when and how should the system be refurbished, should plant be replaced, how can the design of new equipment be improved, when and how often should plant be maintained, how can plant-life be extended using condition-monitoring, and similar topics.

The paper addresses these issues and is in particular concerned with the concepts of data and the types of data needed for the analysis, modeling, and predictive assessment. The paper suggests that it is not efficient and desirable to collect, analyze, and store more data than is required for the purpose intended. The data should reflect the two main processes involved in the plant behavior, namely the failure process and the restoration process. The actual use of data in conceptual terms can be used for one or both of two reasons: assessment of past performance and/or prediction of future performance. While past performance assessments identify chronological changes and determine weak areas for reinforcements or modifications, future predictions estimate the benefits of alternative designs, refurbishments and expansion plans. Currently, data are mostly used for past performance assessments.

Processing of data occurs in two distinct stages. Firstly, field data is obtained by documenting details of failures as they occur and the various outage durations associated with these failures. Secondly, this field data is analyzed to create statistical indices. The quality of data depends on confidence and relevance. Since the failure and restoration processes vary from one component to another, the paper divides equipment into a number of categories, each category being determined by operational functions and/or exposure conditions. Two generic categories are static components (such as transformers and lines) and switching components (such as breakers and isolators). The paper argues that the data needed for each may be different because of the role played in the system and the effect they have when they fail. The paper examines failure processes through dividing failure data into modes, which have a particular impact on system behavior. These failure modes are identified as short circuit failures, open circuit failures, switching failures, multiple failures, and environmental effects. Restoration processes are divided into restoring supply to customers and restoring a failed component to its working state. Care is therefore required to correctly identify restoration times (for predictive reliability assessments component restoration times are required while service restoration times matter for measuring the quality of the service to customers).

In terms of data collection schemes, the authors identify component based versus unit based approaches. The latter is considered worthy for assessing the chronological changes in reliability of existing systems while component based approach is more convenient for predictive applications and reliability characteristics of individual pieces of equipment. The authors divide data into stochastic (as they relate to the random nature of the process) and deterministic (such as certain exposure parameters) and provide ways for measuring the data. Finally the authors review various statistical indices in use (probability of residing in a state, rate/frequency of occurrence of an event, etc.).

It is worth noting that this paper is an overview of data concepts, but does not propose any models or life distributions that include the defined indices as input data or output responses.

M. J. Baxter, A. Bendell, P. T. Manning and S. G. Ryan (1988). Proportional Hazard Modeling of Transmission Equipment Failures

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. 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.

S. Collard, E. Parascos and A. Kressner (1980). Root Cause Failure Analysis in Electric Transmission and Distribution Equipment

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.

G.C. Contaxis, S. D. Kavatza and C. D. Vournas (1989). An interactive package for risk evaluation and maintenance scheduling

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 reverse and levelized risk levels) for the posed problem. A demonstrative case study has been considered.

R. P. Ferguson (1987). Factors affecting the replacement of old transformers

The paper discusses the factors that have to be taken into consideration for replacement of old transformers. These factors are external conditions, internal condition, ancillary equipment, transformer deterioration, aging of insulation, moisture content of oil, maintenance, and finally disposal. The paper concludes that methods for early detection of incipient distress as well as techniques for assessment of the remaining life of a transformer can make a significant contribution. Finally, improved maintenance procedures will promote life enhancement and the availability of practical and realistically priced equipment capable of being fitted to existing transformers to give on-line conditioning and monitoring would be of great benefit.

D. Gilbert (1994). Cable derating and nonlinear load panelboards.

The paper does not relate economic factors to derating decisions. There is nothing methodologically interesting in the paper.

B. I. Gururaj (1984). Overvoltages and disturbances in power distribution networks

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.

R. P. Hoskins, G. Strbac and A. T. Brint (1999). Modeling the degradation of condition indices

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.

M.A. Lebow and M. Vainberg (1998). Asset management planner

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) which 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.

J. P. Mackevich and D. Lynch (1990). An Investigation into Gas Pressure Generation in New and Aged Aluminum Conductor Cable and the Internal Pressure Withstand Capabilities of Joints

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.

K. K. C. Marwali and S. M. Shahidehpour (1998). Long-Term Transmission and Generation Maintenance Scheduling with Network, Fuel and Emission Constraints

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 are 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.

H. S. May (1987). Revitalization and Renovation of 66kv Overhead Lines within NEEB

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.

Meniconi, M., Barry, D.M. (1996). The power distribution: a useful and simple distribution to assess electrical component reliability

The authors propose a power function distribution for assessment of the reliability of semiconductor (transistor) components, and hence is not relevant for our study of distribution systems.

J. Moravek (1994). Benefits of using a Harmonic Monitoring Program

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.

Procacia, H., Cordier, R., Muller, S. (1997). Application of Bayesian statistical decision theory for a maintenance optimization problem

The paper suggests that a rational coherent approach to optimizing equipment maintenance consists of the following. First, one should take expert opinions into account when feedback from experience is limited and combine the expert data with observations in a Bayesian manner. Second, the posterior distributions should be used to calculate the posterior loss associated with each decision. Then for each reasonable decision, the expected posterior loss could be calculated and an optimal decision could be made. The practical focus of the paper is on reliability centered maintenance (RCM) of nuclear power plants.

B. M. Pryor (1987). Factors Affecting the Deterioration of HV Switchgear

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.

J. S. Pugh, L. R. Castro Ferreira, P. A. Crossley, R. N. Allan, J. Downes and M. Burt (1997). The Reliability of Protection and Control Systems for Transmission Feeders

This paper introduces a technique for assessing the reliability of protection and control systems using reliability models and event tree analysis. 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.

W. T. Roberts and L. Mann (1993). Failure Predictions in Repairable Multi-Component Systems

The main points of the paper are as follows. Multi-component repairable systems cannot be modeled by continuous distributions, such as the Weibull. Instead, a multi-component repairable system can be assumed to consist of non-repairable components (replaceable), whose life distribution may be described by a Weibull distribution, and a repair on the whole system will consist of replacing one or more of those components. For the whole system, the power law nonhomogenous Poisson process (NHPP), also known as the Crow model, is recognized as the best model for repairable systems. According to NHPP, within any time interval of interest, a Poisson distribution whose intensity is given as a multiple of a power of the time interval describes the probability of occurrence of failures within that interval. The paper derives maximum-likelihood estimates of the NHPP parameters as (explicit) functions of observable quantities such as number of failures and the age of the system.

A. Rogge (1994). Harmonics: Causes, Problems, Solutions

The article does not discuss the relationship of harmonics to aging, nor is there any discussion of economic consequences of harmonics.

G. J. Salis and A. S. Safigianni (1999). Long-term Optimization of Radial Primary Distribution Networks by Conductor Replacement

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.

M. H. Sanwarwalla and R. J. Weinacht (1987). Aging Management Through Condition Monitoring of ASCo Solenoid Valves and Namco Limit Switches

The paper discusses a program embarked on by Baltimore Gas & Electric Company. The purpose of the program is testing of the ASCo slenoid valves and NAMCO limit switches, which are representative of the models used at Calvert Cliffs nuclear power plant. The paper studies development of baseline criteria against which existing plant equipment condition can be compared. In this connection, the paper discusses selection of representative specimens to be tested, selection of material physical parameters to be monitored, selection of aging parameters, testing, and implementation of the methodology.

S. M. Settje (1996). Transformer reliability some considerations as presented by loss history

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 multi-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.

S. H. Sim and J. Endrenyi, (1988). Optimal Preventive Maintenance with Repair

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.

J. C. Steed (1994). Experiences with Power Transformers in Southern Electric

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.

J. C. Steed (1986). Using Fault Statistics to Monitor Equipment Failure

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.

G. Theil (1987). Estimation of Reliability Indices for the Austrian Voltage Network

The paper presents a method for evaluating reliability indices of transmission networks. 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.

S. T. J. A. Vermeulen, H. Rijanto, F. A. van der Duyn Schouten (1997). The Influence of Preventive Maintenance on the Reliability Performance of Simple Radial Distribution System Parts

The paper considers reliability analysis of protection systems. The major failure modes of protection systems are divided into two categories of failure to operate and unwanted operation mode (maltrips). In the event of failure in sections of the power system, these failure modes could cause more customers suffering from interruption of supply. Both types of failure modes have been cast into a stochastic continuous time Markov chain framework in which multiple protection systems and multiple protected components are considered. Noting that for more complex power systems this approach may result in large number of state variables, a method is developed that aggregates separate Markov models each describing different parts of the power system. The authors report good results for Monte Carlo numerical studies of the method. To study decisions on preventive maintenance, a cost function has been defined that ties the cost contributions of failures and preventive maintenance to the transition events between the states of the Markov model. The technique is applied to evaluate the reliability performance of radial distribution systems.

Note: The fundamental model in this paper is consistent with the way equipment experts think about the problem, but the transition probabilities in this model are stationary, hence the notion of aging assets is not present.

J. D. West (1997?). An Approach to Minimize the Maintenance Cost for an Aircraft Electrical Power Generator

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.

J. H. Witt and Thomas H. Gaidry (1996). Improving Overhaul/Replacement Decisions

The paper discusses the development of a methodology and implementing software that takes into account the reliability trends being exhibited by a equipment in a power generation plant, the effect of prior overhauls, and the expected cost of doing nothing vs. overhaul vs. replacement.

The investigation was motivated by the observation that a large percentage of overhauls were being performed on equipment that exhibited constant, or even growth, reliability characteristics and that the result was nearly always an adverse effect on reliability immediately after the overhaul. Further, the equipment frequently never attained the level of reliability that was exhibited prior to the overhaul (indicating that equipment replacement may have been the more cost-effective decision).

The study consists of three parts: an analysis of representative industry overhaul data to assess the impact of the overhauls on the equipment failure, the formulation of a methodology to enable more cost-effective decisions, testing of the methodology with actual utility data. The results of industrial data analyses using event time lines, Weibull parameters, linear regression plots, reverse attribute tests, and Mann-Whitney tests generally reinforced the notion that too many overhauls were being conducted.

The decision analysis framework contains three strategies, namely, continued operation without any overhaul and replacement, overhaul in a specific year within the remaining life, and replacement of the equipment in a specific year within the remaining life of the equipment. The predicted failure rates for each strategy were used to develop analysis curves (representing expected costs) to determine the optimum decision point. In analyzing reliability data, it was assumed that the failure rate performance of the equipment since its last overhaul could be described by all or portions of the so called “Bathtub” curve and that each portion of the curve could be represented by a set of Weibull distribution parameters.

By applying the methodology to data provided by several utilities, the authors conclude that a significant number of overhauls had been performed even when the equipment were showing constant or even growing reliability characteristics and that this number could be significantly reduced resulting in cost savings for the utility.

3
ANALYTIC METHODS

3.1 Introduction

There are several analytic methods that are currently used to address the issue of aging assets. The methods vary with respect to the assumptions made, the data required, the answers provided, and the degree of sophistication, among other important attributes. It is useful to discuss several of these methods before proceeding to develop an appropriate method for distribution system analysis.

3.2 Engineering Economics: Optimal Replacement Interval

The classic engineering economic analysis of aging assets formulates the problem of selecting the optimal time to replace an aging asset with an identical new one. (White (1989)). (In this formulation, the cost of an asset has two components, the capital cost and the operating (o&m) cost. The decision variable is n, the number of years between replacements.

The following parameters are required:

K=capital or purchase cost of an asset, usually assumed constant over the planning period,

C(t)=annual operating (o&m) cost, for year t, usually assumed to be increasing,

r=discount rate,

S(n)=salvage value of an asset at the end of n years of service, usually assumed to be decreasing.

The *Capital Recovery Cost*, CR(n), is the uniform annual amount equivalent to the investment K made at the end of year 0 and the salvage value S(n) received at the end of year n, and is given by the equation

$$CR(n) = K\ (A|P\ r, n) - S(n)\ (A|F\ r, n)$$

where

$$(A|P\ r, n) = r\ (1+r)^n / [(1+r)^n - 1]$$, which converts a single present value to a uniform flow,

and

$$(A|F\ r, n) = r / [(1+r)^n - 1]$$, which converts a single future value to a uniform flow.

The Capital Recovery Cost decreases with n, or, in other words, the annual capital cost decreases as the number of years the asset is held increases.

The annual operating cost, OC(n), is the uniform annual amount equivalent to the operating costs C(t) incurred at the end of year t, $1 \leq t \leq n$, and is given by the equation

$$OC(n) = [\sum_{t=1}^{n} C(t)\,(1+r)^{-t}\,]\,(A|F\ r, n).$$

The annual operating cost is an increasing function if C(t) is increasing.

The optimal value of n occurs at the minimum of the total cost,

$$TC(n) = CR(n) + OC(n).$$

In most cases, TC(n) is unimodal and n*, the optimal value of n, is unique. See figure 3-1.

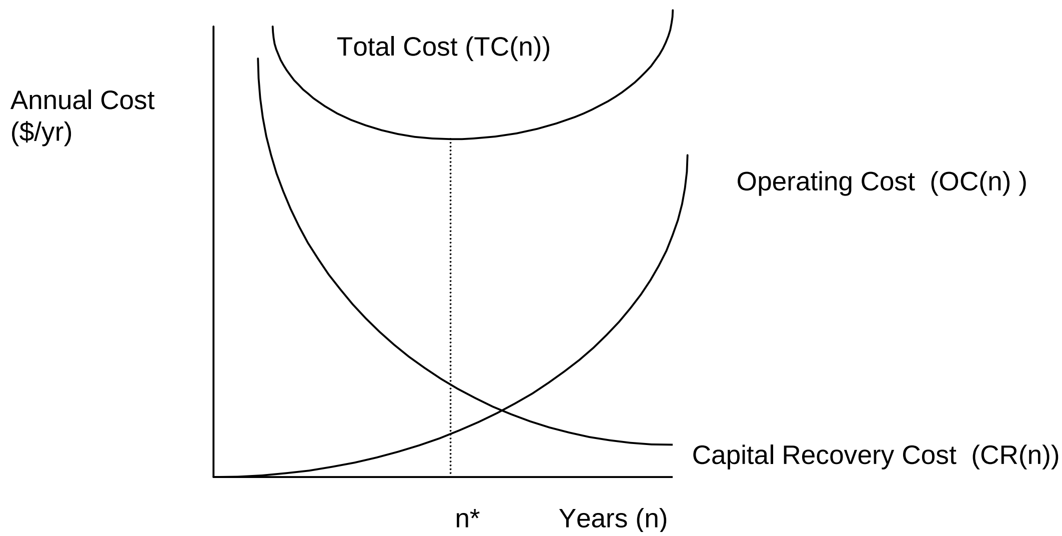

Figure 3-1
Optimal Replacement Interval.

It is also noteworthy that the optimal replacement interval found in this way defines the optimal policy over an infinite horizon. Indeed, that is the problem that this approach is designed to address. It is straightforward to show that the optimal uniform cost over the infinite horizon is equal to the optimal uniform cost over a single cycle (of n* years).

Example. Let K=45,000, let C(1) =6000, C(t+1) = C(t) +1500 + 150 (t-1), r=0.30.

TC(1) = CR(1) + OC(1) = 58,500 + 6000 = 64,500

TC(2) = CR(2) + OC(2) = 33,066 + 6643 = 39,709

TC(3) = CR(3) + OC(3) = 24,777 + 7,277= 32,054

TC(4) = CR(4) + OC(4) = 20,772 + 7,870 = 28,642

TC(5) = CR(5) + OC(5) = 18,477 + 8,429 = 26,906

TC(6) = CR(6) + OC(5) = 17,028 + 8,944 = 25,972

TC(7) = CR(7) + OC(7) = 16,151 + 9,420 = 25,570

TC(8) = CR(8) + OC(8) = 15,386 + 9,840 = 25,226

TC(9) = CR(9) + OC(9) = 14,904 + 10,212 = 25,116

TC(10) = CR(10) + OC(10) = 14,558 + 10,585 = 28,642

Beyond n = 10, TC(n) is monotonically increasing. The optimal replacement interval is n* = 9.

3.3 Dynamic Programming Formulation of the Replacement Problem

For finite planning periods, the engineering economic formulation is not the most convenient. The solution to the replacement problem over a finite planning period, T, requires specification of a policy defined for each year, t, in the planning period, $1 \leq t \leq T$.

Let x = the age of an asset at the end of a year. The solution is found by determining the optimal policy as a function of the pair (x, t), the age of an asset and the time in the planning period.

In the simplest version of the problem there are only two alternatives: at the end of any period, the decision is either to buy a new asset or keep the current one. The optimal decision will be contingent upon the age of the asset and the time when the decision is made.

The following parameters are required:

K(t) = capital or purchase cost of an asset at time t, often assumed constant over the planning period,

C(x,t) = annual operating (o&m) cost, for an asset that will be age x at the end of the year at time t, usually assumed to be increasing with x and independent of t,

R = discount rate (or discount factor $\rho = 1/(1+r)$),

S(x,t) = salvage value of an asset at the end of x years of service at time t, usually assumed to be decreasing with respect to x and often assumed to be constant with respect to t,

R(x,t) = trade-in value of an asset at the end of x years of service at time t, usually assumed to be the same as S(x,t).

The solution to the problem is a *policy,* which specifies the optimal decision as a function of the pair (x,t), so that for any vintage at any time, the planner knows whether to buy a new model and salvage the current asset or keep the current asset.

The optimal decision is found by constructing the optimal cost-to-go, the function V(x,t), which specifies the minimum cost of having an asset from time t to time T, the end of the planning period, given that the asset is age x at time t. The main idea in the definition of V(x,t) is that the optimal cost-to-go is found by determining the optimal policy going forward from time t.

V(x,t) is the solution to the Hamilton-Jacobi equation, which may be expressed in Bellman's form for this problem (Bellman (1955)):

$$V(x,t) = \min \{ [K(t) - R(x,t) + \rho\,(C(1) + V(1,t+1))\,], [\rho\,(C(x+1) + V(x+1, t+1)] \},$$

with the boundary condition,

$$V(x,T) = -S(x,T).$$

The first equation indicates that the optimal policy is determined by selecting the minimum of two costs. The first term is the cost of purchasing a new asset decreased by the trade-in value of the current asset plus the discounted cost of the maintenance of a new asset plus the optimal cost-to-go from the next year (t+1), when the asset will be one year old. The second term is the cost of keeping the asset, which is the discounted sum of the maintenance cost of an asset that will be one year older plus the cost-to-go from the next year (t+1), when the asset will be x+1 years old.

The second equation is a boundary condition. Since the planning period is T years, an asset of age x at the end of T years is worth its salvage value, S(x,T). This is a negative cost.

A straightforward solution procedure is based on solving Bellman's equation using a two-dimensional lattice diagram. The lattice diagram indicates all feasible trajectories emanating from the initial condition $(x_0, 0)$. At time 0, it is possible to buy or keep the current asset, hence there are only two possible successor values to the initial pair $(x_0, 0)$. These are $(x_0 +1, 1)$, if the current asset were kept for one more year, and (1,1), if the current asset were traded in and a new one placed in service. Similarly, from $(x_0 +1, 1)$, the only possible successors are $(x_0 +2, 2)$ and (1,2). From (1,1), the only possible successors are (2,2) and (1,2). These define points in the lattice that propagate until time T.

Example. Let T=5. Let K(t) = 50 for all t. Let r = 0 (no discounting). Suppose x_0=2. Suppose that C,R, and S are independent of t, and as a function of x are given in the following table:

Table 3-1
Example Operating, Trade-in, Salvage Costs as a function of Vintage

X	C(x)	R(x)	S(x)
1	10	32	25
2	13	21	17
3	20	11	8
4	40	5	0
5	70	0	0
6	100	0	0
7	100	0	0

The optimal cost-to-go can be found by working backwards, from the end of the planning period. The lattice diagram (see Table 3-2) indicates the (x,t) pairs that can be reached from the initial condition (2,0).

The boundary conditions yield the following:

V(7,5) = -S(7) = 0

V(5,5) = -S(5) = 0

V(4,5) = -S(4) = 0

V(3,5) = -S(3) = -8

V(2,5) = -S(2) = -17

V(1,5) = -S(1) = -25

Then applying Bellman's equation (with optimal decision noted by *),

Table 3-2
Optimal Cost-to-go and Optimal Decisions as a function of State

V(6,4) =	min {[50-0+10-25]*, [100+0]}=35
V(4,4) =	min {[50-5+10-25]*, [70+0]}=30
V(3,4) =	min {[50-11+10-25]*, [40+0]}=24
V(2,4) =	min {[50-21+10-25], [20-8]*}=12
V(1,4) =	min {[50-32+10-25], [13-17]*}=-4
V(5, 3) =	min {[50-0+10-4]*, [100+35]}=56
V(3, 3) =	min {[50-11+10-4]*, [40+30]}=45
V(2, 3) =	min {[50-21+10-4]*, [20+24]}=35
V(1, 3) =	min {[50-32+10-4]*, [13+12]}=24
V(4, 2) =	min {[50-5+10+24]*, [70+56]}=79
V(2, 2) =	min {[50-21+10+24]*, [20+45]}=63
V(1, 2) =	min {[50-32+10+24], [13+35]*}=48
V(3, 1) =	min {[50-11+10+48]*, [40+79]}=97
V(1, 1) =	min {[50-32+10+48]*, [13+63]*}=76 (tie)
V(2, 0)	= min {[50-21+10+76]*, [20+97]}= 115.

The optimal policies are found by propagating the decisions forward and tracking the (x,t) pairs along the optimal trajectory. In this example, there are two optimal paths. For example, the sequence (2,0) → (1,1) → (1,2) → (2,3) → (1,4) → (2,5), corresponding to the decision sequence B,B,K,B,K, (where B denotes the decision to "Buy" a new asset, and K denotes the decision to "Keep" the existing asset for the next year) is optimal with cost 115. The other optimal policy is given by the sequence (2,0) → (1,1) → (2,2) → (1,3) → (1,4) → (2,5), which corresponds to the decision sequence B,K,B,B,K and costs 115.

3.4 Network Formulation of the Replacement Problem: Linear Programming

The asset replacement problem over a finite planning period can also be formulated as a linear program, using a network model (Hillier (1986)).

In one formulation, the *nodes* of the network are the years in the planning period. In the network model, pairs of nodes are connected by an arc. Each arc is characterized by a cost. The *arcs* correspond to the decision to purchase an asset at the end of the year corresponding to the node from which the arc emanates and to retire that asset at the end of the year corresponding to the node at which the arc terminates. The cost associated with that arc is the minimum cost of that decision.

The linear programming formulation solves the so-called shortest path problem for the network. The decision variables are the *flows* from one node to another, the variable x_{ij}, which denotes the flow from node i to node j in the network. In this formulation, the flows are binary variables (either 0 or 1) because the arc is either in the optimal path or it is not. The constraints on the flows are of three types: (1) the flow out of the originating node (beginning of the planning period) is one; (2) the net flow at an interior node is zero; (3) the flow into the terminal node (final year of the planning period) is one. The objective function is the sum of the products of the flow along an arc multiplied by the cost of the arc. The objective function is to be minimized.

The data required for the network formulation is identical to that of the dynamic programming formulation above.

Example. We solve the machine replacement problem using a network formulation. There are six nodes in the network, corresponding to years zero through five. The arc costs are given in the following matrix:

	Terminal Node				
Origin Node	1	2	3	4	5
0	7	31	61	107	182
1		28	52	82	133
2			28	52	85
3				28	56

4	35

The linear programming formulation is:

min $7\,x_{01} + 31x_{02} + 61x_{03} + 107\,x_{04} + 182\,x_{05} + 28\,x_{12} + 52\,x_{13} + 82\,x_{14} + 133\,x_{15} + 28\,x_{23} + 52\,x_{24} + 85\,x_{25} + 28\,x_{34} + 56\,x_{35} + 35\,x_{45}$

subject to

$$- x_{01} - x_{02} - x_{03} - x_{04} - x_{05} = -1$$

$$x_{01} - x_{12} - x_{13} - x_{14} - x_{15} = 0$$

$$x_{02} + x_{12} - x_{23} - x_{24} - x_{25} = 0$$

$$x_{03} + x_{13} + x_{23} - x_{34} - x_{35} = 0$$

$$x_{04} + x_{14} + x_{24} + x_{34} - x_{45} = 0$$

$$x_{05} + x_{15} + x_{25} + x_{35} + x_{45} = 1$$

$$x_{ij} \geq 0 \text{ for all i, j.}$$

The solution to this problem is not unique. One solution is $x_{01} = 1$, $x_{13} = 1$, $x_{35} = 1$, with cost 115, which corresponds to the solution noted above B,B,K,B,K. Another solution is $x_{02} = 1$, $x_{23} = 1$, $x_{35} = 1$, with cost 115, which corresponds to the solution noted above B,K,B,B,K.

Other network formulations are possible. The well-known transportation model can solve this problem as well. A major drawback to linear programming formulations is the requirement to find minimum path costs prior to invoking the solution algorithm. For a small problem, such as this example, the task is simple. For a large problem, the task can be quite complex.

3.5 Analysis of Existing Methods

The methods discussed above, although somewhat sophisticated, suffer from two essential flaws.

First, they do not address uncertainty. There are important uncertainties associated with the condition of an asset, as it ages and as it reacts to external stresses such as weather, loading, operational errors, lack of maintenance, and other possibilities. The optimal policy should be contingent upon the occurrence of such uncertain events. Moreover, the particular condition of an asset at any time, which is a consequence of the occurrence of such uncertain events, is not captured by the existing methods.

Second, the existing methods are restricted with respect to decision alternatives. The binary alternatives, “Buy” or “Keep,” do not capture such possibilities as doing nothing, performing ordinary maintenance, performing preventive maintenance, or overhauling, in addition to replacing the asset with a new one.

Indeed, the existing methods do not provide a structure whereby it is possible to capture what appears to be the essential policy issue: what is the optimal maintenance and replacement schedule for an asset as it ages? It appears to be insufficient to capture the important information about this problem in a simple function such as C(x,t) which attempts to measure the cost of operating an asset of age x for one year at time t. Therefore, a considerable modification of exiting approaches is needed to provide realistic aging asset analysis tools appropriate for electric power distribution assets.

4
AN APPROACH TO ANALYSIS OF AGING ASSETS

4.1 Introduction

In this chapter, we develop a method for analysis of aging assets that addresses the flaws discussed above. We will illustrate how *stochastic dynamic programming* (e.g., Hillier (1986)) can capture both the effects of uncertain outcomes on the condition of an asset and the value of a range of decision alternatives. Another very powerful method, which we do not explore in this chapter, is a variant on stochastic dynamic programming that takes advantage of any repeating conditions over time. This modeling approach, known as the Markovian decision process (e.g., Hillier (1986)) is especially appropriate for systems whose behavior does not depend on elapsed time directly, but rather on some other variable, such as vintage, that can be renewed or repeated over time. General stochastic dynamic programming is directly applicable to situations where a company is transitioning from an old technology to a new technology and thus is experiencing a one-time transition. Markov decision processes are suitable for analyzing repair and replace policies that renew the same technology, although that restriction can be overcome in some situations. The “Motivating Example” that follows is an example of a situation that involves changing technology as well as maintaining existing equipment.

4.2 Motivating Example: Air Breakers

We solicited utility members to provide actual examples of aging asset problems. The application form can be found in Appendix A of this report. The following problem is one that came to us in response to that solicitation.

4.2.1 Problem Description

We consider the condition of a collection of air breakers installed in the PSEG 138—230—500 kV transmission system. There are either 25 or 26 air breakers installed in the part of the system under study. The breakers are all approximately 30 years old. None has failed yet.

The technology is old, the expertise with respect to this technology and how to attend to these breakers is leaving PSEG for many reasons, the breakers require attention, and the maintenance costs are uncertain.

There are two failure modes for these breakers. The breaker is a fiberglass encapsulated device which contains a pressurized porcelain tube that can literally blow up and shatter, scattering parts up to 700 feet away. This is the *catastrophic* failure mode. In the *non-catastrophic* mode, the breaker can develop air leaks (in either 500psi or 2000psi systems) which will induce a compressor failure (because the compresser must run continually to overcome the leak). This will cause the breaker to open and can cause an interruption. Such interruptions usually occur during cold weather. The cause of this failure mode is worn parts, such as aging gaskets. The critical time for this failure mode is dependent on asset age, and appears to be in the range 8-10 years old. When a non-catastrophic failure occurs, the breaker is taken out of service.

The impact of a failure on customers is variable. Some failures impact no customers, some impact some customers (exactly how many is uncertain) and in some cases—the catastrophic failure mode—all customers could be interrupted for more than 4 hours. Further, when a breaker fails there can be some environmental impacts, particularly a release of SF_6 gas (which is 3.5 times better insulator than air; and the gas is not toxic).

The current maintenance cycle includes yearly inspection and maintenance. In addition, there are special procedures every three, four, six, and nine years. In particular, current policy calls for a *field rebuild* every nine years. The maintenance is costly and labor intensive.

The decision alternatives are (1) maintain the breaker without rebuilding it; (2) rebuild the breaker in place, which costs approximately $150,000; (3) refurbish the breaker in a shop (which, although a well-defined alternative, requires identifying a shop that is able to do the work); and (4) purchase a new breaker, which costs approximately $300,000.

Uncertainties (and relevant parameters describing the uncertainties) that are associated with these alternatives include the following: (1) the failure rate of breakers as a function of age; (2) the failure rate of breakers as a function of time since last maintenance; (3) the failure rate of breakers since rebuild time (which describes whether a rebuilt breaker is “good as new”); (4) the probability of catastrophic failure as a function of age and maintenance history.

4.2.2 Problem Formulation

The problem formulation extends the dynamic programming structure discussed in Section 3 of this report. We begin with the decision alternatives. Instead of the binary decision alternatives {Buy, Keep}, we now permit three alternatives {Maintain, Rebuild, Replace}. That is, at any decision point, it is possible either to maintain the breaker, to rebuild it in place, or to replace it with a new breaker. We suppress the alternative to refurbish the breaker because no shop has been found that can do the work. We further assume that if the breaker is replaced, the new breaker technology performs differently than the current breaker technology.

In addition to characterizing the age of the breaker, the variable denoted x in the earlier dynamic programming formulation, we also characterize the *performance state* of the breaker. We will specify that, prior to making a decision, the breaker can be found to be in one of four distinct conditions: (1) *good*; (2) *problem*, which is an unspecified condition different than good but not failed; (3) *failure*, which means that some work must be undertaken to restore the breaker to operating condition; and (4) *catastrophic failure*, as discussed above.

The performance state of the breaker is uncertain and is assumed to be conditional on the previous performance state of the breaker as well as the age of the breaker. (In this formulation, we will not address explicitly the dependence of performance state on maintenance history. The relationship is implicit only.) We assume that if the prior performance state were *good* then the current performance state can be any of the four states, depending on the age of the equipment. Hence a probability distribution on the performance state must be determined.

Similarly, if the prior performance state were *problem*, then the current performance state can also be any one of the four states. The probability distribution ought to reflect whatever remedies might be applied in response to a problem. Further, one would naturally expect that the probability distributions would differ based on the prior state.

If the prior performance state were either of the failure states, then a specific remedy must be applied that returns the breaker to the *good* state. We also assume that a catastrophic failure requires replacement and adoption, therefore, of a new technology. Hence, probability distributions on performance state vary by technology as well.

Note: The data presented here were developed by the EPRI project team without input prom PSEG. The purpose of this “stylized” example is to illustrate the solution method, not to identify a realistic policy.

These probability distributions are inputs in this formulation. There are four sets of such inputs, corresponding to the two kinds of technologies and the prior state, either *good* or *problem.* Examples of these distributions are given in the matrices below.

Table 4-1
Technology Performance State Probability Matrix (Original Technology, Prior State=*good*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	.90	.85	.85	.70	.55
Problem	.10	.10	.10	.15	.20
Failure	0	.05	.05	.10	.15
C-failure	0	0	0	.05	.10

Table 4-2
Technology Performance State Probability Matrix (Original Technology, Prior State= p*roblem*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	0	0	0	0	0
Problem	.80	.80	.75	.75	.75
Failure	.18	.18	.22	.22	.22
C-failure	.02	.02	.03	.03	.03

Table 4-3
Technology Performance State Probability Matrix (New Technology, Prior State=*good*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	.999	.999	.999	.999	.999
Problem	.001	001	001	001	001
Failure	0	0	0	0	0
C-failure	0	0	0	0	0

Table 4-4
Technology Performance State Probability Matrix (New Technology, Prior State=*problem*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	0	0	0	0	0
Problem	.80	.80	.75	.75	.75
Failure	.20	.20	.22	.22	.22
C-failure	0	0	.03	.03	.03

The matrices above present probability distributions for five time periods. There is no restriction on the model with respect to number of periods. Matrix (b), for example, indicates that if the previous state were problem, then a breaker that is 4 periods old will enter the good state with probability 0, remain in the problem state with probability 0.75 fail with probability 0.22 and fail catastrophically with probability 0.03. Note that all columns must sum to one. These probabilities are denoted p(i, j, τ, x), where i denotes the current performance state (*good, problem*), j denotes the future performance state (*good, problem, failure, catastrophic failure*), τ denotes the technology type (old, new), and x denotes the age of the breaker (time since installation or rebuild). (We note that in this simplified version of the model, we make no distinction with respect to a new breaker and a rebuilt one for the same technology. We will be changing this in the next implementation of the model. We will distinguish the years since rebuild and the years since new separately and report performance state probabilities separately.)

In this formulation, two sets of costs must be specified. First, we require a set of technology decision costs, which are the costs associated with making a decision (maintain, rebuild, replace) for each technology (old, new). These costs may vary with time, and are denoted K(d,t), where d represents the decision and t represents time in the planning period.

Second, we require a set of technology performance costs. These are the costs associated with being in a performance state for each technology type. These costs may vary with age of the breaker and time, and are denoted C(τ,x,t,s), where the notation is as above, and s is the performance state. In the simplest version of the model, the costs are completely stationary and vary with technology only. These costs are shown in the tables below.

Table 4-5
Technology Decision Costs

	Technology	
Decision	Original Technology	New Technology
Maintain	50	500
Rebuild	150	150
Replace	500	500

Table 4-6
Technology Performance Costs

	Technology	
Performance	Original Technology	New Technology
Good	0	0
Problem	50	50
Failure	250	250
C-Failure	1000	1000

With these inputs, the solution to the problem is found by solving Bellman's equation:

$$V(i,\tau,x,t) = \min_d \{ [K(d,t) + \Sigma_s\, p(i, s, \tau(d), x(d)) [C(\tau(d),x(d),t,s) + \rho V(s,\tau(d),x(d),t+1)],$$

where

$V(i,\tau,x,t)$ = minimum cost to go given that the current performance state is i, the current technology is τ, the current breaker is age x, and that the time in the planning period is t.

i = current performance state

x = current breaker age

d = decision

t = time in the planning period

s = subsequent performance state

$\tau(d)$ = technology selected by decision d

x(d) = age of breaker determined by decision d

ρ = discount factor for interest rate r, 1/(1+r).

The model has been implemented using DPL, a decision analysis software package we have used for similar problems. Part of the optimal solution to the problem is shown in a tree format, below. The policy illustrated is conditional on the prior state of the asset. As shown, if the prior state is that the asset is "Old" and "Good" then the optimal decision is to maintain the current asset. If the prior state is "Old" and "Problem" then the optimal decision is to rebuild the current asset. The policy is further defined in subsequent parts of the tree, not shown in the figure. The complete policy for the example is: (1) rebuild the technology if the prior state is "Problem" and the technology state is "Old" or "New", (2) rebuild after the third stage if the the state is "Old" independent of the technology condition\

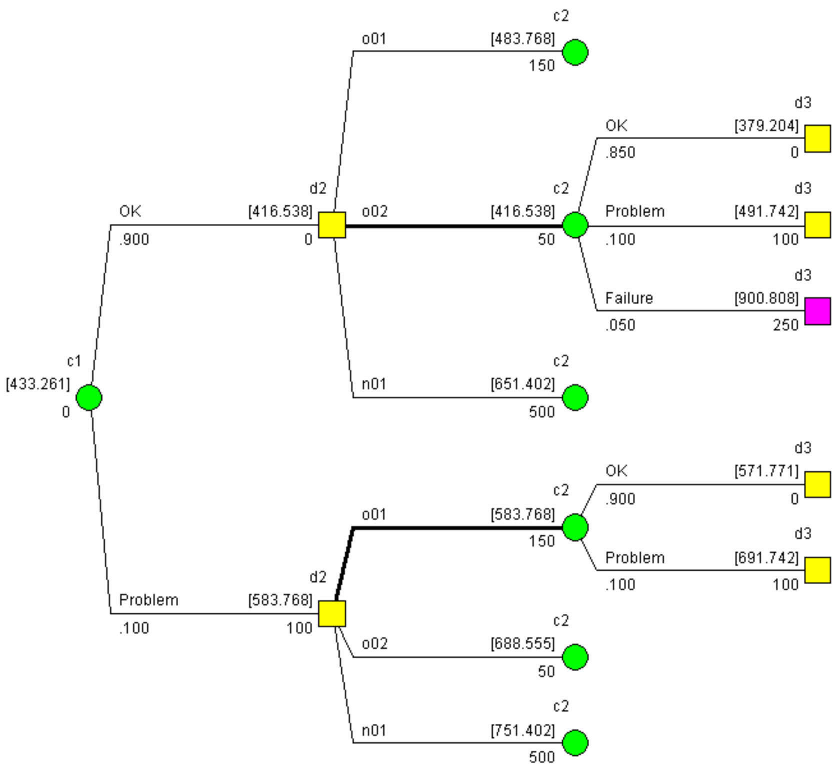

Figure 4-1
Optimal Policy

4.3 Analysis of Proposed Methodology

The structure of this formulation is sufficiently general to permit solution of many aging assets problems. We intend to test the methodology by experiment. In particular, we need to determine whether the data required for the methodology is readily available. We also need to know whether the data required for the methodology captures the essential issues with respect to the behavior of aging assets.

4.3.1 Sources of Data

Ideally, data collection for input to the methodology will be as automated as possible, relying on company data bases, when available, and reasonable defaults, which the user may modify. Assuming that it is possible to capture the behavior of an asset in discrete categories like *good, problem, failure, catastrophic failure,* the natural question is how to find the probabilities that characterize the performance state transitions.

The probability of failure of an aging asset, such as a breaker, can be modeled using standard approaches such as the well-known bathtub curve. An important objective of this project is to document the state of information about failure rates for major subsystems and equipemt types. There are two subtasks within this objective:

1. Identify and assess the quality of existing sources of failure rate data.
2. Document the state-of-understanding of root causes of failure (logic models of failure). This will be based on review of root cause studies and on expert knowledge of the causes of equipment failure.

We have not completed this part of the study. At this time, our research has uncovered only logical models of failure of systems as well as logical models of failure of a single component. We have identified no generally useful sources of data. As noted above, we are working with equipment experts and the electric industry to formulate equipment failure mode models. We expect that these models will be able to reduce the need for extensive and costly data gathering.

4.3.2 Specification of Alternatives

A fundamental assumption we make in developing the methodology is that the decisions available to the asset manager are discrete and include different levels of maintenance, different levels of rebuilding or refurbishing, and replacement. It is the discrete nature of the alternatives that suggests the use of this methodology. If the alternatives are continuously variable, then this methodology may not be useful.

4.3.3 Analysis Under Uncertainty

The methodology is designed to address the consequences of uncertainty, especially with respect to the future behavior of an asset. Since no one is able to forecast with certainty how an asset will behave in response to a maintenance policy or external occurrences, it seems clear that analysis under uncertainty is essential to develop the optimal policy. Any acceptable methodology must address this issue.

5 CONCLUSIONS

We have identified several possible approaches to modeling and creating a methodology to solve the problem of aging assets. We have identified the relevant costs, specified the important phenomena, and proposed an objective to be accomplished in selecting a policy for managing aging assets. We have created a simple model and applied it to a real situation.

We propose to continue the literature search and enhance our existing modeling approach. We are exploring three different implementations of the approach. One implementation uses an existing decision analysis software package, and is the platform used to solve the air breaker problem. There are several drawbacks to using that software package, not least that we must force the existing software to operate in a way it was not intended to operate. The second approach is to apply the optimization implementation we used in the Area Investment Strategy Model. This is the most promising approach, but requires a certain amount of reprogramming. The third approach is to implement the solution procedure using a language like Visual Basic and an interface like Excel. In both of the latter cases the amount of software development is not extensive. A stand-alone dynamic programming module was developed as part of the Area Investment Strategy project. That module can be used directly in this project. Thus only modules for inputs and outputs need to be written.

Therefore, we will explore four questions. First, is there an existing implementation of a reasonable solution to this problem? Second, assuming the answer to the first question is negative, what is the best way for us to implement our approach? Third, what is the best approach we can design to solve this problem? Fourth, what data is available, or can be gathered, to support the designed approach?

We will discuss these issues in the next version of this report

A
Case Studies and Survey

A.1 Case Study Application Form

The following survey form was distributed to the utility advisors of this project. The purpose of this form is to solicit case study problem for the purposes of methodology development. To date one case study has been initiated.

Application Form: Proposed Aging Asset, Repair / Replace Case Study

Instructions

Please use this form to propose specific repair / replace case studies. EPRI will use the proposals to select two case studies to be funded under the aging asset base budget in 2000 and 2001. The case studies will be selected in mid 2000 and will take about nine months to complete.

EPRI will work with the utility to structure and analyze the decision problem. The utility will be expected to provide the required data for the analysis. We estimate that the utility time required for each case will be about one to two person months. EPRI will provide expertise in decision analysis and economic modeling.

This form provides a simple way to describe some key aspects of the proposed repair / replace case studies. EPRI will select the cases based on two criteria: (1) the problems must be real decisions currently faced by your utility, and (2) the problems should have the potential for providing problem insights and a general decision framework that will be useful to other utilities. The case studies will be used to develop an aging asset decision framework and a workshop on the business evaluation of aging asset problems.

To complete the proposal simply type over the text in the three boxes below. You can submit as many proposals as you like. You should keep the proposal fairly short – a paragraph or two in each area. When you have completed your proposals, please email them to me at schapel@EPRI.com.

Steve Chapel

EPRI Project Manager

Description of Decision Problem

1. Problem

In one or two paragraphs describe the decision problem that you face. This problem should be such that your company must make an irrevocable allocation of funds and manpower to solve the problem. The problem should be such that it can be solved by repair / replace decisions associated with some system or subsystem. You should also indicate in qualitative terms the impact of doing nothing.

2. Decision Alternatives

Describe the alternatives for solving the problem. This should include all of the potential repair and replace options. Also provide a rough indication of the cost of each option.

3. Key Uncertainties

Identify what you consider to be the most important uncertainties associated with this decision problem. You don't have to quantify the uncertainties (we will do that later). Just identify the uncertain variables. This might include the likelihood of failure of some systems or subsystems, the costs of systems and subsystems, and the costs or other consequences associated with some failures.

A.2 Survey

A survey form was distributed to utility clients and advisors. That survey is described below including the objectives, instructions and responses we have received to date.

A.2.1 Survey –Objectives and Instructions

Survey Objective:

(1) Identify the important categories of aging assets (this will be used to focus the efforts of the aging asset project),

(2) Gather enough information to start to structure the repair / replace decision problem

Structure of the Questionnaire

There are 3 sets of questions - Causes, Impacts, and Risks. For each set of questions there is a worksheet. Specific questions define the columns.

There are 20 categories of assets in this survey. These define the rows in the worksheet. (Unless specified , survey pertains to Distribution Primary Voltages 35 kV or less)

1. Substation Transformers (Low Side < 15 kV)
2. Substation Transformers (Low Side > 15 kV < 35 kV)
3. Distribution Transformers (pole, padmounted or underground) < 35 kV
4. Substation Breakers, Relays
5. Overhead Conductors
6. Poles
7. Pole mounted Hardware
8. Pole mounted Switches
9. Pad mounted Switches
10. Underground Feeder Cables (including splices and termination's)
11. URD Cables (including splices, elbows and termination's)
12. Aerial Feeder Cables (including splices and termination's)
13. Voltage Regulators / controls
14. Reactors / controls
15. Reclosers / controls
16. Capacitor Banks / controls
17. Phase Shifters
18. Sub-Transmission Hardware (specify) (36-69kV)
19. Transmission Towers
20. Other – specify

Instructions:

(1) Select the five asset categories (from the list above) that you feel are most important (from the perspective of aging assets) and answer the questions for those technologies.

(2) Fill in each of the three assessment spreadsheets - Causes, Impacts, Risks.

(3) Answers go in cells and can be in any combination of numbers and words

A.2.2

A.2.3 Survey - Results

The following three tables present the results of the above survey. The sample is small (five respondents). The survey results are self-explanatory. The first table identifies the causes of problems.

Table A-1
Causes of Equipment Problems

		Causes				
Aging Equipment Problem	**# Companies Reporting**	**Age**	**Maintence**	**Overlaod**	**Weather**	**Other**
1. Poles	4/5	y,y,y,y	y,y,y		y,y	car poles
2. URD Cables	3/5	y,y,y	n,y,y	y,y,y	y,y,y	dig-ins
3. Underground Feeders	2/5	y,y	n,y	y,y	n,y	dig-ins
4. Overhead Conductors	2/5	y,y	?	y	y,y	
5. Voltage Regulators	2/5	y,y	y,y	y,y	y,n	# Operations
6. Pad Mounted Switches	2/5	y,y	y,y	n,n	?,y	
7. Dist. Tranformers	2/5	w,y	n,n	y,y	y,y	
9. Sub. Transformers (low side)	2/5	y,y	y,y	y,y	n,n	
9. Sub Breakers / Relays	2/5	y,y	y,y	n	n	# Operations
10. Aerial Cables	1/5	y	y	y	y	
11. Pole Mounted Hardware	1/5	y	rtf			
12. Reclosers / Controls	1/5	y	y	y	y	
	y -yes					
	n - no					
	? - don't know					
	rtf - run to fail					

The second table presents the impacts associated with each problem.

Table A-2
Impact of Equipment Problems

		Impact		
Aging Equipment Problem	**# Companies Reporting**	**Impacts Lots of Customers?**	**Results in a long ourage duration?**	**Other**
1. Poles	4/5	c,c,c,c	y,y,y,y	
2. URD Cables	3/5	y,c,n	y,y,y	outages due to age, maint.
3. Underground Feeders	2/5	y,y	y,y	outages occur at peak load
4. Overhead Conductors	2/5	n,c	tn,y	
5. Voltage Regulators	2/5	c,c	tn,y	
6. Pad Mounted Switches	2/5	c,y	tn, depends on sys. config.	
7. Dist. Tranformers	2/5	tn,n	n (overhead), y(network); y	
9. Sub. Transformers (low side)	2/5	y,y	y,y	can cause political problems
9. Sub Breakers / Relays	2/5	y,y	n,n	
10. Aerial Cables	1/5	y	n	outages due to load, rain
11. Pole Mounted Hardware	1/5	c	y	
12. Reclosers / Controls	1/5	c	tn	
	y -yes			
	n - no			
	c - can			
	tn - typically no			

The third table presents the perceived risks. It is worth noting that the range of values reported for cost to repair or replace is within a relatively large range.

Table A-3

Risks of Equipment Problem

		Risks			
Aging Equipment Problem	**# Companies Reporting**	**P(failure)?**	**P(failure) change with age?**	**Cost (repair or replace)**	**Time to repair**
1. Poles	4/5	0.1%, <1%	low 0-25 years, increases for >25	350-10,000	4-24 hrs
2. URD Cables	3/5	7%, 2-4%	increases 5% yr.	300-12,000	4-24 hrs
3. Underground Feeders	2/5	6%	increases 5% yr.	5,000-15,000	2-4 days
4. Overhead Conductors	2/5	2.4% / mile	yes	splice 100, 7000 / mile for 1-phase, 15,000 / mile 3-phase	2+ hrs
5. Voltage Regulators	2/5	1.5%	unknown	10,000+	2-12 hrs
6. Pad Mounted Switches	2/5	1.8%	unknown	4,000	2+ hrs
7. Dist. Tranformers	2/5	0.3%	increases 5% yr.	1,500-3,000	6-12 hrs
9. Sub. Transformers (low side)	2/5	0.45%	doubles ever 10 years	150k-1000k	24+hours
9. Sub Breakers / Relays	2/5	unknown	unknown	30,000	4 hrs
10. Aerial Cables	1/5	6.5%	increases 10% yr.	5,000-15,000	2-4 days
11. Pole Mounted Hardware	1/5				
12. Reclosers / Controls	1/5	0.9%	unknown	2,000+	3+ hrs

B
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