Optimal Replacement of Underground Distribution Cables

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***Abstract*—This paper presents a general decision model that enables utilities to generate business cases for asset management policies, with a specific application to underground distribution cables. The model takes a life-cycle costing approach that enables corporate financial managers and regulators to assess the multi-year financial impacts of maintaining specific classes of power delivery infrastructure assets, such as underground cables. The model specifies the evolution of the condition of the asset population over time, the various decision alternatives that are available, including testing, and the basic data needed to support the decision model. The decision model represents the dynamic process of underground cable deterioration mathematically, using a set of equations that provide a forecast of future deterioration. The dynamic equations describe the evolution of cable condition probabilistically – given the current cable state, there will be a probability distribution of states in which the cable might be observed the next time it is inspected. The model represents the information obtainable from diagnostic tests and determines when it is cost-effective to use them. The model also specifies the data needed for decision-making. The model uses a dynamic programming formulation to solve for the optimal asset management strategy.**

***Index Terms*—Business economics, Business planning, Management decision-making, Power cable testing, Power cables, Power distribution economics, Power distribution planning , Power system economics, Power system planning, Reliability management**

I. INTRODUCTION

Increasing pressure from both customers and regulators to maintain and enhance service reliability, while at the same time controlling costs, has put many utilities' distribution businesses in a classic dilemma of conflicting objectives. For that reason, asset management has become an increasingly important aspect of corporate business strategies. A significant focus of EPRI's asset management research in recent years has been to develop a rational basis for selecting repair or replacement options for specific classes of equipment that balances the risks of equipment failure against the costs of continued maintenance or capital replacement. This paper discusses methods for making these decisions with a focus on an asset of particular concern to many utilities, their underground distribution cables.

This paper describes a set of analytical models for dealing with the complexities of the underground cable management decisions. This framework:

- systematically captures the factors that influence the cost effectiveness of cable management policies
- identifies the key information needed for making good decisions
- provides an objective way to choose among decision alternatives
- enables calculating the cost and performance consequences of the policies.

Managing a population of aging equipment requires considering three distinct phenomena: 1) representing the dynamic processes of failure and replacement of the equipment; 2) projecting changing failure rates as equipment ages; 3) balancing the costs of equipment failure with replacement options to come up with the least-cost equipment replacement policy.

This paper presents a basic framework for asset management [4] that is applicable to many kinds of equipment. The following elements of this decision model are addressed in this paper:

- Objective, Decision Options, and Optimal Policies
- Condition Dynamics and State Definitions
- Failure Rates
- Expert Judgment
- Testing
- Data requirements

II. OBJECTIVE, DECISION OPTIONS, AND OPTIMAL POLICIES

The decision model addresses the question of what to do with cable assets as a function of their age and condition. The objective is to minimize the lifecycle cost of maintaining the underground cable inventory. The lifecycle cost comprises the total costs of the decisions taken throughout a multi-year time horizon on a present value basis. The decision options available for a given cable segment may include inspect/test, repair, rejuvenate using silicone injection, or replace. The unit to which these options may be applied is an underground cable segment, typically the span from manhole to manhole. The decision model represents these decisions as depending on the state of an underground cable segment. The specification of a decision for each state is called a policy. In general, the optimal policy will trade off the risk and cost of a cable failure, which increases with age and deteriorating condition,

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against the cost of rejuvenation or early replacement.

III. CONDITION DYNAMICS AND STATE DEFINITIONS

In general, the state summarizes information about an underground cable segment at a given point in time that is sufficient to forecast its future behavior. A number of alternative representations of the state are possible, depending upon what information is available to make decisions; thus choosing a representation of the state is a design decision. The state can include both observable and unobservable information. In the decision model presented in this paper, the observable state of an underground cable segment has two components: its age and the number of previous failures it has experienced. Based on prior experience, this information provides a reasonable basis for deciding among the various options available.

The condition of underground cable segments is usually not directly observable; however, it may be inferred from diagnostic tests. The condition of the insulation of a paper-insulted lead cable (PILC) is a relevant unobservable state variable (table 1). (For an extruded cable, the condition of the neutral is also modeled.) [4]

TABLE 1
DEFINITION OF INSULATION DEGRADATION CONDITION STATE LEVELS

Insulation Degradation Condition State	Description
No Degradation	Insulation good as new
Mild Degradation	Small water trees (WT) (<10% of ins. thick.) or voids in insulation
Mod Degradation	Moderate WT (lengths 10-30% of ins. thick.) or voids in insulation
Severe Degradation	Severe WT (> 30% of ins. thick.), large voids (PD inc. < 1.5 Vo)

Over time, the insulation of an individual cable segment deteriorates as it experiences thermal loading, water ingress, and other stressors. The deterioration rate depends on the cable type, initial installation, as well as these influencing factors. The dynamic process of insulation deterioration is represented mathematically, using a set of equations that provide a forecast of future cable conditions.

Because the evolution of the cable state cannot be predicted with certainty, the dynamic equations describe it probabilistically – given the current segment state, there will be a probability distribution of states in which the segment might be observed at some future time. The random evolution of the state results from three factors:

- The degradation processes proceed randomly.
- There is uncertainty about a segment's current condition because it cannot be observed directly.
- The state does not necessarily represent all aspects of an underground cable segment's history relevant to predicting its future because 1) the amount of information in a utility's records is limited for reasons of cost or practicality and 2) a complex definition of the state can make the dynamic equations mathematically intractable. Thus, two segments with the same state might in fact have different histories, and differences in their future condition would appear random because information needed to predict them are not available.

The probabilistic evolution of insulation condition is displayed in table 2, which shows the probability of finding a segment in a given condition at different ages [4].

TABLE 2
DYNAMICS OF INSULATION DEGRADATION CONDITION LEVELS FOR PILC

Fraction of Cable in Each State

Age	No Degradation	Mild Degradation	Moderate Degradation	Severe Degradation
10	95%	4%	1%	0%
20	75%	10%	10%	5%
40	60%	20%	10%	10%
60	50%	20%	20%	10%

Diagnostic tests can provide some information about unobservable conditions. However, their usefulness is limited for two reasons: 1) tests are generally not completely definitive in identifying a cable's condition and 2) testing is costly. Thus, whether or not to test is a decision, a part of the overall asset management policy for underground distribution cables. These points are discussed further below.

Ultimately the deterioration of an underground cable segment can lead to its failure. Figure 1 illustrates the interactions among the factors that determine a segment's failure rate.

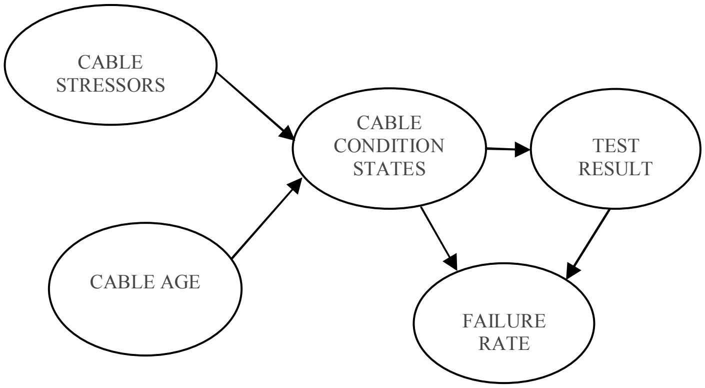


Figure 1 Factors Determining Failure Rates

IV. FAILURE RATES

The failure rate at a particular age, the *hazard rate*, is the probability that a cable segment that has survived to that age fails in the next time period. Ideally, the hazard rate can be determined empirically from a utility's maintenance records; in practice, however, there are many difficulties with the underlying data, particularly lack of detailed information tracking cable installations, degradation, and subsequent failures.

Furthermore, purely empirical estimates of failure rates often fail to behave in plausible ways, due to random fluctuations in the data; for instance, the observed hazard rates (diamonds) in Figure 2 show considerable random variation. In developing hazard functions from empirical data, the estimates should obey two properties: 1) underground cables are more likely to fail as they get older, and 2) hazard rates for ages t and t+1 are not too different from each other. In practice, noise in estimated hazard rates should not drive the treatment/replacement decision.

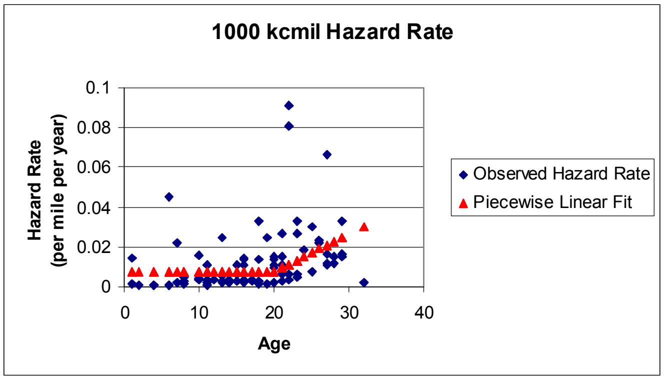


Figure 2 Estimated Hazard Functions, Based on Observed Failure Data

A statistical model of the hazard rates, which fits a function to the observed data, can control the random variations [2], [5]. There are many potential models used in analysis of reliability data. A piecewise linear model is particularly well suited for underground cables. Based on experience, the hazard rate for underground cables tends to remain fairly constant for a period of time after installation, the *steady-state* period, and then it increases during a *burnout* period that reflects the effect of aging:

$$h(t) = s + \max[0, m(t-T)]$$

where $h(t)$ is the hazard rate at age t, s is the steady-state hazard rate, T is the age at which burnout begins, and m is the burnout rate. The triangles in figure 2 represent a piecewise linear fit to the data, with $s = 0.0075$, $T = 20$, and $m = 0.0019$.

V. EXPERT JUDGMENT

As illustrated in figure 1, the cable failure rate depends on a number of additional factors besides age. However, these factors are not well represented in cable data that currently exists, for several reasons:

- Many utilities have not collected detailed information to track cable failures.
- Because equipment replacement occurs near the end of its life, even with improving data collection processes, a considerable lag will occur before information tracking the full lifetime of equipment becomes available.
- Gathering certain kinds of data, such as insulation condition, is very costly, especially in getting adequate sample sizes needed for statistical precision.

Given the limitations of statistical data analysis to estimate key relationships among parameters of the decision model, use of expert judgment provides an important element of the analysis. Among the parameters estimated by experts [4] are the differential effects on the hazard rates of the following factors:

- condition states of the cable insulation and the neutral
- environmental and operating stressors
- past failures

In addition, the following parameters have also been estimated by experts:

- the proportion of the cable population in each condition state as a function of age
- the accuracy of test protocols is revealing the true condition of the insulation and neutral.

TABLE 3
EFFECT OF INSULATION CONDITION STATE ON HAZARD RATE FOR PILC

Insulation State	**Steady state hazard**	**Onset of burnout**	**Doubling time**
	Multiplier		
No Degradation	1.00	1.00	1.00
Mild Degradation	1.00	0.50	0.85
Moderate Degradation	1.00	0.35	0.60
Severe Degradation	1.00	0.15	0.40

For example, table 3 [4] illustrates adjustments to the piecewise linear hazard rate parameters due to degraded insulation condition. For instance, if a PILC cable segment has mild insulation degradation, then the steady-state hazard rate s is unchanged, the onset of burnout occurs at $0.5T$, and the doubling time, the time it takes for the hazard rate to reach $2s$, decreases to eighty-five percent of the value for the segments with no degradation.

Essentially, at present, statistical data analysis supports estimating the basic hazard functions with some level of specificity by cable type; the remainder of the parameters have primarily been estimated by experts. With systematic data collection efforts across the industry, it should be possible in the future to validate the expert judgments with statistical data analysis.

VI. TESTING

Diagnostic tests can play an important, though somewhat controversial, role in managing underground distribution cable assets. They can provide some information about the condition of the insulation and neutral, which are not directly observable. However, three issues limit the usefulness of tests. First, tests are generally not completely definitive in identifying a cable's condition [1]; however, even an inaccurate test may provide information useful for asset management decisions. Second, the relationship between test outcomes and hazard rates is not well established. Finally, testing is costly (and in some cases may cause failure of the equipment). In fact, these three issues are linked together, and the controversy over cable testing is basically a question of whether the value of the information, even if somewhat inaccurate, outweighs the cost of obtaining it

Whether or not to test is a decision, a part of the overall asset management policy for underground distribution cables. That is, a test has value only if its outcome would lead to making a different decision. The decision model can propose a state-based testing policy; the tests are applied in states where results have value exceeding the cost of the test. [1]

The model of testing uses several overall principles. First, the decision model separates specification of the test outcome from the action taken based upon it. In contrast to much current industry practice, this principle permits optimizing the asset management policy as a function of test outcome, rather than pre-specifying the decision. Second, the decision model represents test protocols, a bank of related tests applied to an individual cable segment at one time, rather than individual tests (see table 3 [4]). This representation conforms to current industry practice that takes advantage of the different kinds of information available from different tests (e.g. withstand, partial discharge, power factor, etc.). Third, test outcomes are specified in terms a claim about condition state they diagnose.

TABLE 3
TEST PROTOCOL FOR PILC

Description of Insulation Degradation Test Protocol
Withstand or diagnostic test
PD test measures local degradation (tracking, etc)
Damage caused by PD depends on location of PD
Different types of test voltages (DC, 60 Hz, VLF, DAC)
Standards available for some tests (include criteria to assess cable condition)
Bulk degradation measured by tan delta or power factor (extent of WT damage)

This specification was chosen because it is fairly easy to understand, it applies across many kinds of tests, and it conforms to an industry practice of rating cable condition on a qualitative scale (typically with 3- or 4-points). Thus, test accuracy can be specified as the probability that the test says the condition is “X” when in fact the true condition is Y, where X and Y represent condition states (see Table 4 [4]).

TABLE 4
TEST ACCURACY FOR PILC

	Test Protocol Outcome			
Actual Condition	"No Degradation"	"Mild Degradation"	"Moderate Degradation"	"Severe Degradation"
No Degradation	0.80	0.10	0.05	0.05
Mild Degradation	0.20	0.40	0.30	0.10
Moderate Degradation	0.15	0.30	0.35	0.20
Severe Degradation	0.05	0.10	0.15	0.70

Finally, it is assumed that the model does not remember the outcome of a previous test bank. This assumption greatly simplifies the state dynamic equations by not requiring them to represent the unobservable state. It is a reasonable assumption under two conditions: 1) test intervals are fairly long relative to the speed of degradation, or 2) the action taken as a result of the test changes the cable’s condition so that the previous condition is no longer relevant. However, the representation of test information over time remains an area of possible extension of the decision model.

VII. DATA REQUIREMENTS

The basic data required to support the decision model for underground cables are summarized as follows:

- Hazard rates as functions of age and other state variables. Estimates of the basic hazard rate as a function age developed from utility-specific or industry-wide data. Adjustments of the hazard rates, using either statistical analysis, if relevant data is available, or expert judgment if not, for the effects of past failures, degraded conditions, and the presence of environmental or operating stressors.
- The consequences of a rejuvenation decision on the state, again using either actual data or expert assessment.
- Probability distributions of the insulation (and neutral) condition as a function of age, usually provided by expert assessment.
- Testing protocols and their accuracy, given by likelihood functions, again usually provided by expert assessment.
- Cost per cable segment for the following: replacement, rejuvenation, failure, testing, and operation as a function of condition, found in utility records or provided by expert assessment.

VIII. SOLUTION USING DYNAMIC PROGRAMMING

The decision model discussed in this paper finds the optimal policy for replacing aging equipment using *dynamic programming*, which is discussed in detail in prior EPRI reports, e.g., [1], [2], as well as in many text books. The dynamic program is formulated as a set of equations representing the cost of the decision made in each state in terms of the immediate cost of that decision and the cost-to-go of subsequent decisions made as the state evolves.

The optimal solution to a dynamic program is a specification of a decision for each state, a *policy*, which satisfies these equations. The optimal policy is found using a mathematical programming algorithm called *Policy Iteration*. It is an iterative procedure that starts with a trial policy and seeks to improve the policy by changing the decisions in each state. Policy iteration is a very efficient algorithm, that can efficient search through millions of potential solutions and usually converges to the optimum within a very small number of iterations.

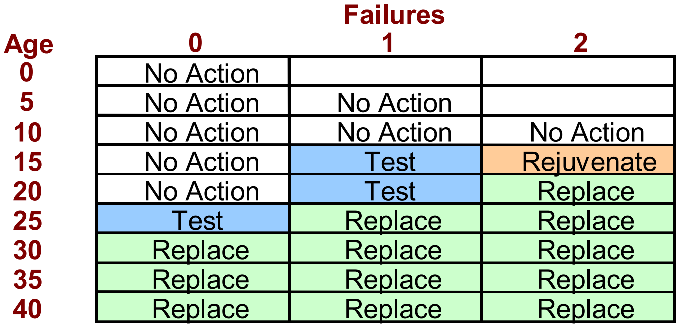
IX. REPRESENTATIVE RESULTS

An example of an optimal policy from the decision model is given in tables 5 and 6 [4]. The optimal decision depends on the observable state (age and number of prior failures) and on the test result. (Note that these results are specific to the cable data used in the analysis and do not constitute a recommendation for other kinds of cables; the decision model is capable of analyzing many scenarios.) In this example, the optimal policy is to replace a cable segment at age 30 with no prior failures, 25 with one failure and 20 with 2 or more failures. It is also optimal to rejuvenate cables at age 15 with 2 or more failures. Testing is optimal at age 25 with no failures and at 15 or 20 with one failure. Table 6 shows the optimal decisions based on the test outcomes.

Testing is optimal at age 25 with no failures and at 15 or 20 with one failure. Table 6 shows the optimal decisions based on

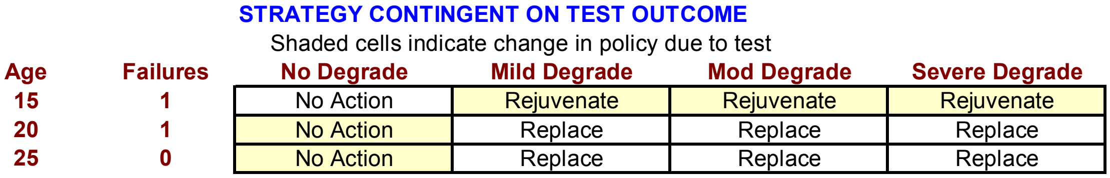
the test outcomes. If the test results in a finding of no insulation degradation, no action is necessary. If the test finds mild, moderate, or severe degradation, it is optimal to rejuvenate at age 15 and to replace at 20 or 25.

TABLE 5
EXAMPLE OPTIMAL POLICY WITH TESTING



Age	Failures 0	1	2
0	No Action		
5	No Action	No Action	
10	No Action	No Action	No Action
15	No Action	Test	Rejuvenate
20	No Action	Test	Replace
25	Test	Replace	Replace
30	Replace	Replace	Replace
35	Replace	Replace	Replace
40	Replace	Replace	Replace

TABLE 6
EXAMPLE CONTINGENT TEST STRATEGY



STRATEGY CONTINGENT ON TEST OUTCOME

Shaded cells indicate change in policy due to test

Age	Failures	No Degrade	Mild Degrade	Mod Degrade	Severe Degrade
15	1	No Action	Rejuvenate	Rejuvenate	Rejuvenate
20	1	No Action	Replace	Replace	Replace
25	0	No Action	Replace	Replace	Replace

X. CONCLUSIONS

EPRI has developed a decision framework that enables utilities to generate sound business cases for asset management policies. This framework takes a life-cycle costing approach that enables corporate financial managers and regulators to assess the multi-year financial impacts of maintaining specific classes of power delivery infrastructure assets, such as underground distribution cables.

The analytical tools presented in this report share a basic framework for decision-making that specifies the evolution of the condition of the asset population over time, the various decision alternatives that are available, including testing, and the basic data needed to support the decision model. The decision model represents the dynamic process of underground cable deterioration mathematically, using a set of equations that provide a forecast of future deterioration. The decision model is flexible with respect to what data is available for decision-making.

Using this decision model can reduce costs for managing critical power delivery assets. Case studies have indicated 25%-35% lifecycle cost savings for optimal policies compared to policies currently in use by utilities. Optimal policies can also improve reliability (e.g., SAIFI) by planning replacements of vulnerable equipment prior to failure.

XI. ACKNOWLEDGMENT

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XIII. BIOGRAPHIES

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